Report Rapport

Atomic Energy Control Board
P.O. Box 1046
Ottawa, Canada
K1P 5S9

Commission de contrôle de l'énergie atomique
C.P. 1046
Ottawa, Canada
K1P 5S9

INFO-0113

WELDING OF CARBON STEEL VESSELS WITHOUT POST WELD HEAT TREATMENT

by

M. Gibb
S.R. Bala

A research report prepared for the
Atomic Energy Control Board
Ottawa, Canada

RESEARCH REPORT

January 1984

DISCLAIMER

The Atomic Energy Control Board is not responsible for the accuracy of the statements made or opinions expressed in this publication and neither the Board nor the authors assume liability with respect to any damage or loss incurred as a result of the use made of the information contained in this publication.

WELDING OF CARBON STEEL VESSELS WITHOUT POST WELD HEAT TREATMENT

ABSTRACT

The methods available for the repair welding of carbon steel vessels without post weld heat treatment and with particular reference to service in a sour environment have been reviewed.

All the available techniques have the common aim of providing adequate properties in the weld metal and Heat Affected Zone without the need for a full post weld stress relief. The heat that is required to provide the necessary metallurgical changes comes, therefore, from an alternate source. The two sources used are heat from suitably placed subsequent weld passes or from localized external heat sources.

The technique presently being used by Ontario Hydro to repair vessels subject to sour service utilizes both a high preheat and a welding technique which is designed to temper the Heat Affected Zone formed in the base material by the first weld pass. This technique is an improvement over the 'half bead' techniques given in the ASME XI code and has been shown to be capable of reducing the hardness of the heat affected zone to an acceptable level.

Certain recommendations have been made which could improve control of the technique presently used by Ontario Hydro and provide measurable parameters between procedural tests and the actual weld repairs.

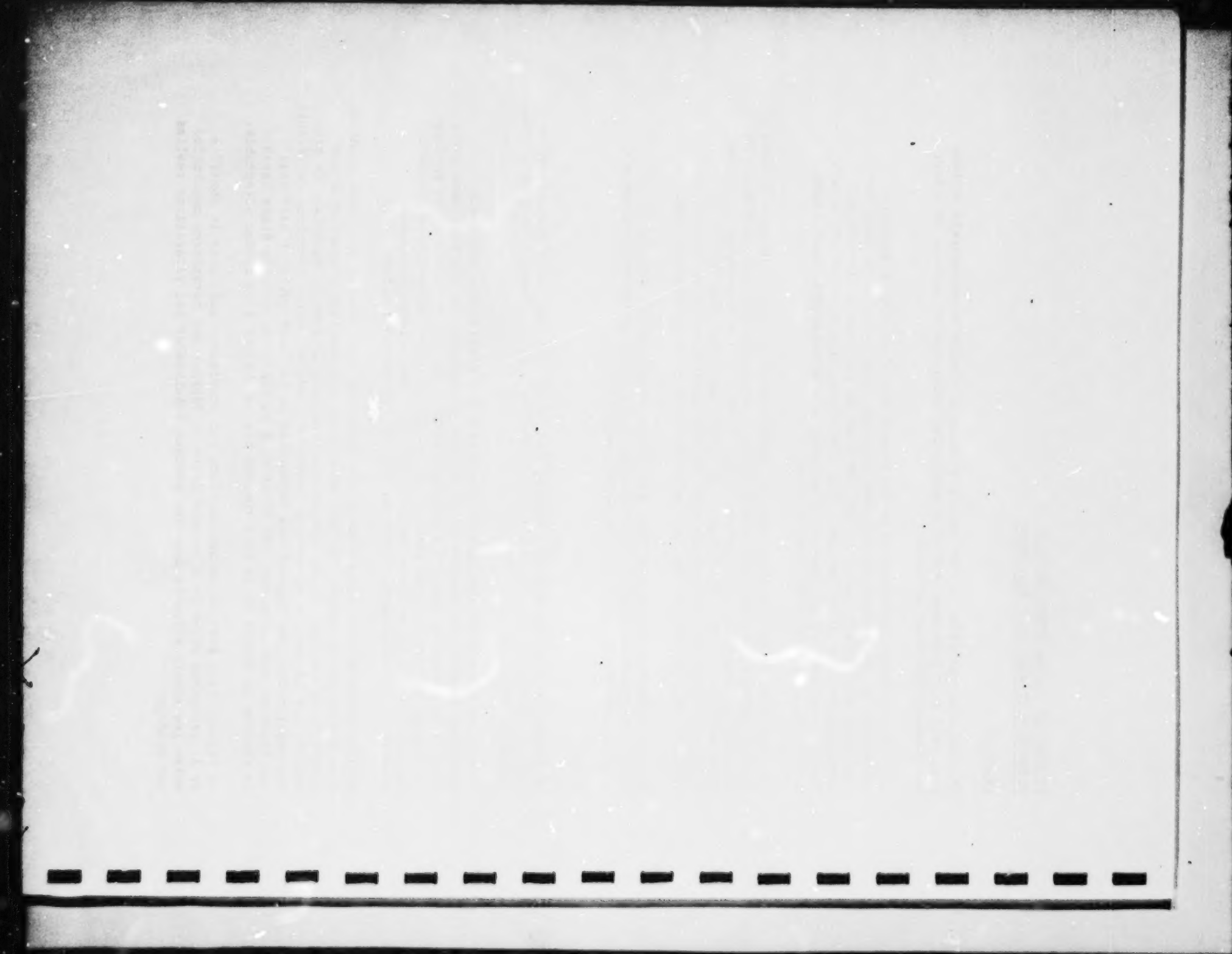
RÉSUMÉ

Le rapport traite des méthodes disponibles de soudage sans chauffage ultérieur pour la réparation des cuves d'acier au carbone particulièrement dans un milieu gazeux acide.

Toutes les techniques disponibles ont pour but d'assurer des propriétés adéquates du métal de soudure et de la zone touchée par la chaleur, sans avoir recours au processus complet d'affranchissement de la contrainte après soudage. La chaleur nécessaire pour assurer les modifications métallurgiques provient donc de deux autres sources, soit actuellement des cordons de soudure ultérieurs judicieusement placés ou des sources externes déterminées.

Ontario Hydro utilise actuellement une technique pour réparer les cuves soumises à un milieu gazeux acide, qui fait appel à un préchauffage intense et à une technique de soudage qui est conçue pour tempérer la zone du matériau de base touchée par la chaleur du premier cordon de soudure. Cette technique représente une amélioration par rapport aux techniques de la "demi-perle" ("half-bead") qui figurent dans la norme ASME XI et on a pu démontrer qu'elle était capable de réduire la dureté de la zone touchée par la chaleur à un niveau acceptable.

Le rapport fait état de recommandations qui pourraient améliorer le contrôle de la technique actuelle d'Ontario Hydro et fournir des paramètres mesurables entre les essais stipulés dans les marches à suivre et les réparations réelles par soudage.



INDEX

		Page No.
A.	INTRODUCTION	1-2
B.	HEAT TREATMENT	3
	1. Preheating	4
	2. Postweld Heat Treatment	5
C.	REPAIR METHODS	8
	1. Half Bead Technique	8-9
	2. CEGB Two Layer Refinement Technique	10
	3. Weld Bead Tempering of the HAZ	11
	4. CEGB Cold Welding Technique	12
	5. CRC Local Post Weld Heating	13
	6. Other Local Tempering Methods	13-14
	7. Mechanical Stress Relief	14-15
D.	ONTARIO HYDRO TEMPER BEAD TECHNIQUE	16-17
E.	A REVIEW OF CORROSION SUSCEPTIBILITY OF WELD METAL AND HEAT AFFECTED ZONE IN SOUR ENVIRONMENT	18
	1. General	18-19
	2. Susceptibility of HAZ to SSC	19-24
	3. Susceptibility of Weld Metal to SSC	24-25
	4. Inferences on the Susceptibility to SSC of C and C-Mn Weldments in Sour Environments	25-26

		Page No.
F.	TOUGHNESS EVALUATION	27-28
G.	TYPES OF DEFECTS THAT COULD OCCUR DURING REPAIR WELDING	29
	1. Hydrogen Cracking	29-30
	2. Lack of Fusion and Penetration	30
	3. Slag Entrapment	31
	4. Porosity	31
	5. Solidification Cracking	31
H.	DISCUSSION	32
	1. Weld Repair Techniques	32-37
I.	CONCLUSIONS	38
J.	RECOMMENDATIONS	39
	1. Improvement in Welding Procedural Control	39
	2. Corrosion Tests	40
	3. Fracture Assessment	40
References		41-43
Bibliography		44-47
Appendix 1	Ontario Hydro's Procedure	

A. INTRODUCTION

Ferritic materials fabricated to form pressure vessel components in thicknesses greater than 37mm are required by the relevant design codes to be stress relieved prior to service. This heat treatment is performed to relieve the residual stresses resulting from forming and welding operations, reduction in stresses being achieved by creep relaxation at a temperature of approximately 620°C. The heat treatment also has the effect of tempering the microstructure so that hardened areas, normally confined to the heat affected zone surrounding the weld, are softened to give a more ductile and tougher microstructure.

Critical components such as reactor pressure vessels are normally designed for a certain life before replacement. However, during service, defects often appear either due, amongst others, to incorrect design, fatigue, corrosion, or because the environment was more aggressive than expected. Frequently, initial fabrication errors are also found due, in part, to the increased sophistication of Non-Destructive Examination techniques used during 'in service' inspection.

To repair such defects presents a problem in the respect that in many cases it is not always possible to perform a stress relief treatment on components in situ. This results from the risks involved in differential thermal expansions leading to possible distortion, overheating of critical components, or loss in strength leading to buckling.

In pressure vessels where there is no anticipated corrosive environment, the major considerations for repair welding are the provisions of a satisfactory heat affected zone (HAZ) microstructure from the viewpoint of reducing the risk of hydrogen induced cold cracking and the maintenance of adequate toughness to reduce the risk of brittle fracture. Cold cracking is dependent upon the following factors; a susceptible microstructure, hydrogen content, stress level and temperature.

When using low hydrogen procedures, much evidence exists to show that microstructures with hardnesses below HV 350 in the HAZ are adequate to prevent the onset of cold cracking. As a consequence, repair procedures exist which prescribe preheating/post-heating temperatures and electrode control in order to limit the HAZ hardness to HV 350 and below. Additionally, techniques are given for the reheating of the HAZ in order to recrystallize or temper it and, therefore, provide a tougher microstructure. The item that remains is the residual stress, resulting from the welding repair operation.

In an environment which can cause sulphide stress cracking (SSC), the microstructure becomes more significant as a hardness value of HV 350 may not be sufficient to suppress the onset of sulphide stress cracking. Such conditions exist in Canadian Heavy Water Plants where the corrosive environment is aqueous hydrogen sulphide (H_2O-H_2S). As sensitivity to sulphide stress cracking increases with material hardness, the relevance of hardness control to avoid it is plainly evident, and design to avoid its onset has been almost universally based on the adoption of the Rockwell HRC 22 (HV 250) criteria.

It can thus be seen that welding procedures designed to facilitate in situ repair based upon a hardness criteria of HV 350, are unsatisfactory in an environment which promotes sulphide stress cracking.

This report, based on a survey of current literature and known practices, reviews and discusses the techniques available for the weld repair of ferritic steels with particular emphasis on the conditions existing in the sour service environment of heavy water plants.

B. HEAT TREATMENT

As a background to the various methods available for performing weld repair, it is essential to describe the types of heat treatment that may be applied to weldments and why such heat treatments are necessary.

In this section, heat treatments will be discussed from the point of view of those that are appropriate to this review and which are applicable to P1 type steels with compositions similar to ASTM A516 Grade 70. Reference will be made to the equilibrium diagram for the Fe-C System which is shown in Figure 1.

Using a steel composition of A516-70 type with a carbon content of approximately 0.23%, then it can be seen from Figure 1 that above the AC_3 line at a temperature >850°C, the structure of the steel will be completely austenitic. During slow cooling, the structure changes with reduction in temperature through the AC_3-AC_1 lines (i.e., between 850-690°C, a region known as the intercritical) with a percentage of the austenite transforming into ferrite. Below AC_1, the remaining austenite then transforms into a mixture of ferrite and iron carbide known as pearlite. As a result, the final structure of the slowly cooled steel consists basically of the two phases, ferrite and pearlite, mixed in a percentage which depends upon the carbon content of the steel.

In a weldment, the slow cooling rates necessary to provide the above do not occur since, in essence, a small bead of weld metal is rapidly cooled on contact with a colder mass of parent material or a mass of previously deposited weld metal which is considerably cooler than the molten weld bead being deposited. Consequently, the parent material which sees the heat of welding, the heat affected zone, and the weld bead itself cool at an accelerated rate which can produce a mixture of structures containing hardened constituents such as martensite

and bainite in the base material. In many cases, such structures are undesirable to the overall quality and integrity of a structure and, therefore, steps are taken to minimize such microstructures, many of these relating to heat treatments in one form or another.

1. Preheating

Under certain conditions, steels of the C-Mn type are susceptible to a form of cracking in the Heat Affected Zone (HAZ) of a weld which is known by various names; such as hydrogen-induced cracking, underbead cracking, cold cracking or HAZ cracking. Hydrogen may be present in deposited weld metal as a result of breakdown of contaminants in consumables, such as moisture in electrode coatings. The term 'cold cracking' is used to indicate that this form of cracking is found to occur only when the joint has nearly or completely cooled to room temperature. In many cases, this problem can be overcome by the application of preheat. Preheat is beneficial in preventing cold cracking for two reasons; firstly the slower cooling rates from welding may reduce the tendency for the formation of susceptible microstructures in the HAZ. Secondly, the preheat maintains the HAZ at a temperature where susceptibility to cracking is reduced, giving time for the hydrogen level to drop by diffusion away from the joint. This form of cracking occurs only in susceptible microstructures in the presence of hydrogen and under tensile stress. For the C/Mn steels, a reasonable indication of the presence of such microstructures is given by hardness exceeding HV 350, which corresponds to the formation of microstructures containing martensite and in some cases, bainite.

It has been found that the response to varying cooling rates of different steels in the C-Mn range, can be conveniently expressed in terms of carbon equivalent formulae, in which the chemical composition of the steel is expressed as the sum of the effect of different elements on hardenability. The most commonly used expression is that

given by the International Institute of Welding viz;

$$CE = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Cu + Ni}{15}$$

2. Postweld Heat Treatment

(1) Low Temperature Hydrogen Diffusion

This consists of increasing a predefined preheat to a low temperature hydrogen diffusion temperature of approximately 250°C and holding for a period to allow diffusion of hydrogen away from the joint.

(2) Stress Relief

Stress relief consists of heating a weldment to a temperature below the lower critical point - AC_1, usually in the range of 480°C to 670°C, such that there is no transformation to austenite and the ferrite-pearlite structure and grain size remains unchanged.

Welded structures have residual stresses near the yield strength whether or not there was external restraint during welding. These stresses can cause a number of difficulties in a weldment. The likelihood that any of these difficulties will occur is dependent, of course, upon the combination of steel composition, welding process, weldment design or service conditions. In C-Mn steels, relief of stresses can, however, result in the following improvements:

(a) Minimized susceptibility to fracture development particularly under conditions which call for high notch toughness.
(b) Improved dimensional stability.
(c) Increased resistance to corrosion, especially stress-corrosion cracking.

With regard to weldments, the adoption of a stress relief heat treatment is to relieve these stresses by the dual process of recovery and relaxation through the temperature range and to soften hardened regions by tempering.

(3) Tempering (Drawing)

Raising the temperature of hardened steel to any temperature below the lower critical temperature is called tempering. The heat-affected zone close to welds, made with insufficient preheat in medium-carbon steels, cools so rapidly as to be hardened. While the HAZ is above its critical range during welding, it consisted of austenite containing many times as much carbon in solid solution as is soluble at room temperature. During fast cooling, the austenite changes largely to martensite: the hard body-centered tetragonal form of steel.

In general terms, when the temperature is raised during tempering, the zone containing martensite undergoes three changes:

(a) Martensite changes to ferrite (body-centered cubic structure) with the precipitation of fine carbides from the super-saturated tetragonal lattice.

(b) Any retained austenite that has not changed to martensite during fast cooling changes to ferrite and carbide.

(c) The minute carbides in the martensite and the larger carbides in other constituents, such as fine pearlite, increase in size.

The temperatures at which changes (a) and (b) occur are not known precisely but, in carbon steels with about 0.7% C, they occur at temperatures up to 250°C. The growth in size of carbide particles is continuous as the temperature is raised. Change (c) seems to account for the major drop in hardness on tempering; that is, the hardness of lightly

tempered martensite depends upon a fine dispersion of carbide particles on each crystal plane, which hinders slip and thus raises hardness while reducing ductility. Tempering at higher temperatures coarsens the carbide particles and reduces their number, thus reducing hardness. The hardness after tempering depends primarily on the tempering temperature, time at temperature being of secondary importance.

(4) Grain Refinement (Normalizing)

Grain refinement of a weldment occurs by heating the structure or weld area to a temperature above the AC_3 for the particular composition. For a steel containing 0.23C by weight, this temperature would be in excess of 850°C. Above this temperature, the ferrite pearlite is transfered into single phase austenite and, providing the temperature is held within approximately 50°C above the A_{C3} for a certain length of time, a fine grained structure of ferrite and pearlite with increased resistance to fracture, results on cooling.

As an example, the most common requirement for a grain refinement treatment in C-Mn weldments is for those fabricated by the electroslag welding process. The electroslag process, which is particularly attractive for welding thick sections with a single-run weld, brings with it problems of excessive grain coarsening in the HAZ close to the fusion boundary. Also, the cast structure of the weld metal itself has relatively poor fracture properties compared with those in plate material of similar composition. In some applications, the fracture toughness of the HAZ and weld metal of electroslag welded joints is regarded as unacceptable in the as-welded condition. Considerable improvements in fracture properties for these regions can be obtained by a grain refining treatment after welding since such a treatment produces a considerable reduction in grain size in both weld metal and HAZ.

C. REPAIR METHODS AND FEATURES

Repair methods follow normal welding practice with adjustments, where possible, to simulate the effects of post weld stress relief.

Several methods have been developed for repair or new construction without post weld heat treatment:

1. Half Bead Technique.

The technique was developed in the U.S.A. specifically to give good HAZ toughness without post weld stress relief and is mandated by ASME Boiler and Pressure Vessel Code for repair of nuclear power plant equipment. This is achieved by tempering the HAZ in the weldment being repaired by the heat from subsequent passes. Described in detail in ASME XI[(1)] and based on the ASME III[(2)] repair welding procedure, the technique, which is limited to the shielded manual metal arc (SMAW) process, consists of milling or grinding a suitable cavity and laying one layer of SMAW buttering using a 2.4mm (ASME XI) diameter electrodes. Following completion of the buttering layer, half its depth is then ground off and a subsequent layer using larger electrodes of 3.2mm diameter is deposited. The repair area is then filled using electrodes no larger than 4.0mm diameter.

The cavity is over-filled, and ground back, to ensure that the last passes remaining in the structure have been tempered. The ASME codes lay down very strict controls on the specific technique:

(1) qualification of the welding procedure by welding a test coupon which simulates the actual repair in terms of restraint and access;

(2) use of electrodes specially processed and stored to yield a very low deposited weld metal hydrogen content (i.e. low coating moisture content);

(3) control of the shape and size of the excavated cavity to ensure adequate access for manipulation during welding;

(4) use of a high preheat temperature (177°C) with adequate means to ensure it is maintained for the full duration of the repair operation; and

(5) a low temperature post-weld baking treatment at 232-288°C to assist hydrogen diffusion.

The principle behind the technqiue is to deposit a first layer of weld metal of consistent thickness using small electrodes and no weaving which results in a thin but relatively hard heat affected zone (HAZ). After grinding to remove half the bead and even the thickness of the first layer, the second layer is made, using the same no-weaving technique and an electrode one size larger than that employed in the first layer. The HAZ of the second layer thus lies partly within the fusion zone of the first layer, and partly overlies the first layer's HAZ. The intended result is that the highest temperature portion of the second layer's HAZ will lie entirely within low carbon deposited first-layer weld metal, where grain coarsening associated with it will be of little consequence. The outer portions of the second layer's HAZ where peak temepratures are lower, coincides with the base metal hardened by the first layer of the weld, refining it to a finer grained, low hardenability structure, or tempering it. Thus, the entire heat affected volume of the base metal will effectively display a normalized or tempered structure after completion of the two layers. The high preheat of 177°C maintained throughout the repair welding operation and continued until the low temperature heat treatment, serves along with the low hydrogen control of the electrodes to prevent hydrogen induced cold cracking.

The half bead technique has been critized for its operation and complexity and the difficulty of determining if half the first layer has been removed. It has been reported[3] that it proved rather difficult to obtain reproducible measurements in the cavity when the repair area is maintained at a preheat of 177°C.

2. C.E.G.B Two Layer Refinement Technique.

This technique was developed by the C.E.G.B. (in the U.K.),[4] specifically for reclamation and repair of ½ Cr ½ Mo ¼ V castings and its primary aim is to enable these to be welded with minimum risk of reheat cracking during subsequent postweld stress relief. Such castings could be very prone to reheat cracking, and this procedure was, therefore, developed specifically to prevent this by destroying all course-grained H.A.Z. regions or at least to break up the austenite grain boundary regions by intercritical thermal cycles induced by subsequent weld passes. This is accomplished using basic coated low hydrogen 2 Cr-Mo electrodes by depositing the first layer using 3.25mm electrodes with a stringer bead technique with at least 50% overlap. Weaving is not permitted. Welding current is closely controlled and the subsequent passes are made with 4.0mm electrodes with the tip of the electrode directed at the toe of the previous pass. The weld is then dressed to remove surface defects such as notches or undercut and, unlike the half bead technique, is then post weld stress-relieved.

Control of the relative heat inputs of the two layers was shown to be essential for refinement success and considerable effort was expended in demonstrating the variations in welding parameters that could be tolerated while still achieving satisfactory results. The variations in heat input ratio are given for various preheat levels, using basic coated electrodes which may well vary if other classes of electrodes were used.

Whilst refinement differs from tempering, the work performed in developing this technique, introduces a more precise method of depositing the weld beads.

3. Weld Bead Tempering of the HAZ

A theoretical investigation into the use of temper bead welds to temper the HAZ at the toe of welds was published in the Scandinavian Journal of Metallurgy[5]. Although directed at the regulations which limit HAZ and weld metal hardness because of corrosion considerations for initial fabrication, it is equally applicable to repair situations. When hardness limits of HV 280,HV 300 or HV 325 cannot be met by suitable preheat or welding conditions, then deposition of temper beads has been suggested as a means of reducing the hardness of the HAZ. The procedure is indicated schematically in Figure 2, showing two temper beads (black) in the lower sketch. If the beads are properly positioned with respect to the fusion line, the outer (A_{C1}) countour of the HAZ produced by the temper bead should just touch the fusion line of the last filler pass as indicated in the upper sketch in Figure 2. The material re-austenitized by the temper bead would then be weld metal, which is not likely to develop high hardness peaks due to its lower carbon content, while the HAZ remaining from the last filler pass would be tempered at a temperature below the lower critical temperature.

The shape of the fusion and transformation boundries and the width of the transformed zones sketched in Figure 2, will clearly depend on welding conditions, i.e., heat input.

The work consists of applying the results of isothermal and pulsed tempering experiments to calculated thermal programmes to predict the results of a tempering operation. For the low preheat levels of approximately 20°C used in the investigation, it was shown that the temper pass required very precise positioning for successful results.

4. CEGB Cold Welding Technique

The Welding Institute (U.K.) gave the following account of the above technique in reference (6).

This method has been developed recently by the CEGB to enable repairs to be made to ½Cr ½Mo ¼V components during service. A prerequisite of such repairs is that they should be made without preheat or postheat (although preheat may be used in practice), give a repair free from hydrogen cracks, be amenable to ultrasonic inspection (thus precluding the use of austenitic materials), and also give a repair with sufficient high temperature ductility to survive ~20,000 hr in service, i.e., until the next major planned outage, when the component could be replaced, or repaired using more established procedures, specifically developed by CEGB for Cr Mo V materials. It has been demonstrated that a satisfactory repair can be made by using a low carbon ½Cr ½Mo ¼V basic electrode, which has a low hardenability, together with a carefully planned welding procedure which maximizes refinement of microstructures by heat from subsequent passes. The procedure developed requires that electrodes are baked to give a hydrogen level of less than 6ml/100g of deposited weld metal. The floor of the preparation is welded with 3.2mm dia. electrodes, and all other welding is done with 5.0mm electrodes. In order to obtain maximum HAZ refinement, a current of 140A, with a nominal travel speed of ~3mm/sec was specified. There is at present no performance evaluation data for such repairs, although it is understood that the procedure has been used for non-critical in-service components and these are being closely monitored.

5. C.R.C. Local Post Weld Heating.

In order to satisfy the NACE HRC 22[7] hardness requirements in the HAZ's of low heat input, all position circumferencial welds in thick-walled gas transmission pipelines, C.R.C. - Crose International of Houston, Texas, U.S.A. have developed a traveling heater[8] which consists of a series of heating torches mounted on a single traveling carrier and spaced apart in sequence. The heaters are passed along the newly welded joint and locally heat the metal and temper the hard areas of the HAZ.

Parameters; e.g., heat intensity and travel speed are determined during pre-production qualification and then subsequently used for production. The patent description also claims to reduce heat induced stresses in electric arc welding of large workpieces such as thick walled pipe. This latter claim must be questioned as it is well known that localized heating results in high residual stresses. The most that could be realisticaly claimed is that the heating modifies the residual stress pattern around the welds. The most probable reason for using this technique as opposed to a full circumferencial stress relief is that it is faster and, therefore, more suited to the high production environment of an offshore pipe lay barge.

6. Other Local Tempering Methods

(1) Electrodes, usually the cellulosic type, originally developed for preheating before welding as manufactured by Lastek Engineering of Maidenhead, U.K,[9] could be used for local tempering of weld HAZ's. However, a problem with the use of these electrodes would be that it is difficult to be certain that they have been used correctly, as their use leaves a less obvious, inspectable trace than a conventional weld bead.

(2) Heating with exothermic powders (Fe_2O_3 + Al) has been used for stress relief, but this could prove time-consuming if much weld had to be heated, and care would be needed to achieve the correct temperature.

(3) The use of an arc process without filler material such as Gas Tungsten Arc Welding or Plasma Arc Welding to provide local heating is possible. Difficulties may exist in determining the areas heated as there will be no weld deposit but this would not be a problem with an automated technique.

(4) Local heating with electric or gas heaters similar to the CRC system is possible, but problems could be encountered with temperature measurement. High residual stresses could result from localized heating, and tempering should be considered as the only possible benefit.

7. Mechanical Treatments

(1) Mechanical Stress Relief - Overloading.
It has been suggested[10] that whilst no evidence exists to confirm the effects of mechanical stress relief on stress corrosion, it is to be expected that, if residual stresses are a major factor, mechanical stress relief by overloading will be beneficial. There would, however, be no thermal tempering of the HAZ and major practical difficulties may be experienced, such as foundations being inadequate to support the loads imposed during a hydrostatic test. The temperature for overloading must be considered very carefully to ensure that failure by brittle fracture does not occur.

(2) Vibratory Techniques.

Claims have been made that relief of residual stresses can be achieved by vibratory techniques. Evidence on this subject is slight and that which exists suggests that the treatments are of limited effect. Some users have apparently achieved beneficial results from applying vibratory equipment to welded components where the problem has been one of maintaining dimensional stability during subsequent machining. Vibratory treatment cannot be regarded as being equivalent to thermal or overload stress relief treatments and is not suited for cases where failure by fatigue, brittle fracture or stress corrosion, is a possibility.

D. ONTARIO HYDRO TEMPER-BEAD TECHNIQUE

The Ontario Hydro procedure PM-636-83 reproduced as Appendix 1 is basically a hybrid of the ASME XI temper bead and CEGB two pass grain refinement techniques.

Features of the procedure are:

(1) Procedure qualification.

(2) Welder performance qualification.

(3) Strict limitation on procedures use.

(4) Specification of SMAW process only with the use of a specially conditioned E7018 electrodes.

(5) Specification of welding technique, including the electrode size for first, second and subsequent layers. A requirement for the heat input of the second layers to be twice that of the first layer.

(6) Magnetic particle inspection is performed on every layer, and grinding of the layers is permitted to produce a suitable surface. If grinding is performed, the first layer thickness shall not be reduced by more than one half.

(7) Contingency measures are provided for preheat and post weld bake requirements should the welding be interrupted for any reason.

Tempering, and not refinement, is the object of the procedure as indicated by the heat input ratio of 2.0, which is considerably less than that indicated in the CEGB work where for 100% refinement of the HAZ with preheat of 230°C, the ratio required would be 3.2 to 3.4.

It must, however, be noted that the "Record of Procedure Qualification Tests" (Page 12 of Appendix 1) does not give details of:

(1) Heat inputs used for each layer, arc travel speeds are not quoted.

(2) Layer thickness or the distance between passes (pitch) which can act as a control.

E. A REVIEW OF STRESS-CORROSION CRACKING SUSCEPTIBILITY OF WELD METAL AND HEAT AFFECTED ZONE IN SOUR ENVIRONMENT

1. General

For the last three decades, the subject of cracking in steels for oil country tubular goods and gas transmission line pipes, due to the wet H_2S environment (sour service) has been extensively investigated. However, relatively few studies have been carried out for pressure vessel steels and the weldments used for the sour gas applications. During the nineteen fifties, it became apparent that steels under tensile stresses could fail in a brittle manner when exposed to environments containing wet H_2S. Such failures had become a major concern in the gas industry and have led to the field tests of stressed specimens of various steels. The case histories and the field tests have led to the publication of NACE Standard Materials Requirements MR-01-75 (1980 Revision)[7].

One of the important stipulations of this standard is that to avoid sulphide stress cracking (SSC) of carbon and low alloy steels in sour environments, the hardness of these steels should not exceed HRC 22 (HV 250). Carter and Hyatt[11], in an extensive review published in 1973, cite considerable evidence, including industrial experience, supporting the NACE criterion of HRC 22. However, they note also that stressed steels with hardnesses below HRC 22 will sometimes fail in a brittle manner in H_2S environments by a distinctive "blister cracking" or "stepwise cracking" (SWC) mechanism unlike classical SSC. Classical SSC is a type of cracking which results from the absorption of embrittling hydrogen, a by-product of the corrosion process, and cracking occurs transverse to the direction of tensile stress. Thus, cracking in sour environments can be regarded as taking place by one of two mechanisms[12] viz:

(i) by an 'active path' process (SSC), in which crack propagation takes place primarily perpendicular to the tensile stress;

(ii) as a result of hydrogen pressure (step wise cracking, also called hydrogen induced cracking or hydrogen pressure cracking).

The latter mechanism is related primarily to the inclusions in the steels, and can occur without any tensile stress. Thus, the selection of a clean steel to avoid SWC does not ensure freedom from SSC if appropriate conditions (stress, hardness, microstructure) are present for its occurance.

In repair welding of heavy water towers, the inclusion content of the parent steel is not a controllable variable and, therefore, susceptibility of the parent steel or heat-affected zone to step wise cracking is expected to remain essentially the same, irrespective of the repair welding procedure employed.

2. Susceptibility of HAZ to SSC

There are several factors influencing the successful fabrication of the welded joints; such as, material thickness, thermo-mechanical properties of the steel, welding procedure which includes welding process, consumables, joint constraint, heat input and preweld and post weld heat treatment. There is limited discussion on the effects of some of these on the SSC of weldments in sour service, and as might be expected, they exercise their influence through their effect on hardness and microstructure.

Carbon equivalent (CE) is an empirical relation based on the steel chemistry used to account for the influence of carbon and other alloying elements on the hardenability or cold cracking susceptibility of steels during welding. Among the most widely used formulas

are those established by the International Institute for Welding (IIW) and by Ito and Bessyo. The formulas are listed below:

$$CE = C + \frac{Mn}{6} + \frac{Cr + V + Mo}{5} + \frac{Cu + Ni}{15} \qquad \text{(IIW)}$$

$$P_{cm} = C + \frac{V}{10} + \frac{Mo}{15} + \frac{Mn + Cr + Cu}{20} + \frac{Si}{30} + \frac{Ni}{60} \qquad \text{(Ito-Bessyo)}$$

The IIW carbon equivalent is based on tests carried out on steels with carbon greater than 0.18 wt%, whereas the P_{cm} was established for steels with carbon in the range 0.07 to 0.18 wt%.

Based on the knowledge that the factors influencing cold cracking and SSC, as well as their mechanisms are similar, attempts have been made to correlate SSC susceptibility of the HAZ to carbon equivalents. Thus, Taira et al[13] considered the case of welded line pipe, where the HAZ becomes considerably harder than the base metal, especially in the girth-welded joint because of the very low heat inputs. This hardened area (HV 270-290) was typically found to be more susceptible to SSC, using the three point loaded bent beam test, the NACE tension test and the four point bending test. The critical hardness to avoid SSC, was primarily determined by the H_2S partial pressure in any welding method, and was HV 250 and HV 280, respectively, for 1.0 atm and 0.1 atm H_2S gas partial pressure. Generally, SSC tendency of the HAZ is greatly reduced when CE is below 0.35 in control-rolled microalloyed line pipe steels with hardnesses < HRC22. For steels with CE higher than 0.35, application of preheat and control of interpass temperature is required to prevent the formation of SSC susceptible microstructure such as martensite and bainite.

Taira et al stated that, for a pipe line steel, the critical stress (Sc) for SSC (i.e. resistance to SSC) primarily depends on the material hardness and that SSC of any region (base metal, HAZ or weld metal) is possible, depending on microstructure, at hardness values < HV 250.

Heat input is an important welding parameter affecting susceptibility to SSC since low heat inputs and associated fast cooling rates contribute to high hardness due to the formation of martensite in the HAZ of carbon steel weldments. To prevent this, the correct heat input and interpass temperature should be determined for each welding case.

Figures 3[13] and 4[14] illustrate the effect of carbon equivalent and welding conditions on the hardness of the HAZ. The plots indicate that the untempered regions of the root and/or cap passes of the pipe girth welds have a higher hardness (> HV250) than the tempered regions (< HV250) of the weld joint. It should be noted that SSC of weldments was reported by many investigators to have occured preferentially in these regions of high hardness in the HAZ.

Kihara et al.[15] reported that PWHT of weldments at 580°C was not effective in increasing the value of the threshold stress of the steel weldments in high strength steels (ultimate strength 500-800 MPa) exposed to an H_2S environment. This presumably was due to the particular composition of the steels chosen, containing a significant amount of microalloying elements (V and Ti). It should be noted that the authors reported these conclusions on the basis of observations made on small test pieces. In practice, however, PWHT has been shown to not only reduce hardness, but also reduce residual stresses in complex or large welded strutures with beneficial effects[15] [16]. Bates[16] indicated that post-weld heat treatment of steels can be beneficial in preventing SSC of A537 steel weldments.

Any shop fabricated ferritic steel pressure retaining component will have been post weld heat treated (PWHT) during manufacture if it is more than 37mm thick. The PWHT temperature for carbon-manganese pressure vessel and piping steels is usually about 620°C. Post Weld ("stress relief") heat treatment as applied to ferritic steels not only reduces residual stresses, but also tempers the low

temperature transformation products in the heat affected zone and helps the diffusion of hydrogen away from the weld zone. However, the generally specified hardness value of HRC 22 maximum for the prevention of SSC means that all welded carbon steel fabrications require PWHT regardless of their thickness.

Application of preheat is another approach to control the hardness of the HAZ. Thus, in an Ontario Hydro study[17] of the repair welding procedure employing the temper bead technique, it was found that as the preheat increased, the peak HAZ hardness decreased, and to achieve peak hardness of HV 250, a preheat of 232°C was required for the A516 Gr. 70 steel used. In this study, Ontario Hydro also subjected four point bent beam stress corrosion test specimens from repair welds to environments typical of the hot and cold Girdler-Sulphide process conditions for producing heavy water. The repair welds were representative of the area of the heavy water towers where temper bead welding technique has been proposed as the method for repairing erosion corrosion damaged areas. Welds subjected to testing included both properly made specimens with hardness less than HV 250 and weldments made with an incorrect preheat temperature and a measured weld toe hardness of at least HV 290 (HRC 28). None of these specimens, loaded beyond yield stress, displayed any tendency to cracking which suggests that a properly applied temper bead weld repair should provide satisfactory service under sour conditions.

The effect of preheating on the SSC sensitivity of weldments in sour environments was also studied by Kihara et al. Their findings showed that a preheat temperature between 100 and 150°C considerably improved the SSC resistance of the HAZ in a newly developed Cr-Mo-Al high strength steel. This is shown in Figure 5. The results also suggest that the effect of preheat on the SSC of HAZ depends on the steel composition.

One key aspect in which a non-stress relieved repair weld is different from a shop fabricated, stress relieved weld, irrespective of the HAZ hardness is the presence of residual stresses in the former. The deleterious effect that these might have on SSC susceptibility of HAZ (assuming its hardness is less than HV 250) has been qualitatively commented on several times. However, few studies have been carried out to demonstrate it, probably because of difficulties in isolating the effects of lowered residual stresses and modified microstructure (lower hardness) accompanying stress relief.

Thus, Taira et al[13] measured greater than yield strength magnitude residual stresses in the HAZ of girth welds in line pipe. However, in small scale tests, there was no evidence of SSC in HAZ. Since residual stresses are difficult to retain in small specimens, large scale tests were being planned by these authors.

The effect of residual stresses on the SSC of weldments was also looked at by Tanaka et al[18], using a modified implant test and their results, performed on line pipe steel, are illustrated in Figure 6. The results show no clear difference between the SSC susceptibility of as-welded or stress relieved heat-affected zones. Although the mechanism of SSC after stress-relief heat treatment was not clear, they report that precipitation of carbides or nitrides and grain boundary embrittlement may have been responsible in counter balancing the beneficial effects of reduced residual stresses.

Kihara et al.[15] investigated the performance and SSC susceptibility of constrained weld specimens of high strength steels (HY80) in H_2S environment. The test specimen was a constrained plate with a slit that varied in depth to change the degree of residual stress by welding. The specimens were immersed in 0.5% acetic acid saturated with H_2S for three weeks and the distribution of cracks was observed. They indicated that the susceptibility to SSC increases as the effective constrained width increases and consequently, as the

residual stress caused by welding increases. Kihara et al showed, rather unambiguously, that the residual stress is an important factor in determining the SSC susceptibility of the weldments.

3. Susceptibility of Weld Metal to SSC

Consumables used to fabricate vessels are defined by code requirements, i.e. the weld metal strength must be equal to or exceed the base metal strength and adequate toughness, usually measured by Charpy impact testing, must be achieved. These codes are concerned only with the mechanical properties without accounting for corrosion resistance in environments such as hydrogen sulphide.

Kotecki and Howden[19] and Ebert[20] investigated the performance of pressure vessel steel weld joints in a wet sulphide environment. The welds were fabricated by submerged-arc welding using welding wires of varying composition along with fluxes of different types. Their findings indicate that weld metal manganese and silicon contents, and consequently its hardness, varied substantially by varying the arc voltage with bonded fluxes. At high voltage it was possible to produce welds of 2 percent manganese and 1 percent silicon, starting with a wire of less than 1 percent manganese and little silicon. It is possible for a weld metal of this composition to have a hardness in excess of HV 250. Kotecki and Howden's wet sulphide exposure tests (NACE T-1F-9 Standard test method) showed weld metal SSC when weld metal hardness values were generally > HV 210. The tests were performed without the application of load, assuming residual stresses of yield point magnitude were present in the weld metal.

Consequently, they point out that SSC may occur readily with these weld metal hardnesses in a wet sulfide environment as severe as the NACE-T-1F-9 Test under welding residual stress alone. Their work, limited to Submerged Arc Welding, illustrates the importance of the selection of welding consumables and the correct application of

welding procedure to limit weld metal hardness. It should be noted that weld metal hardnesses lower than the values cited are readily achievable.

Kotecki and Howden also investigated the effects of hardspots and the arc restarts on SSC of submerged arc weld metals. They showed that the hardspots initiated cracking in welds with overall hardness > HV 200 and cited that a PWHT at 1150°F for the submerged arc weldments they studied was ineffective in reducing SSC susceptibility of local hard spots to crack initiation. It has also been speculated that the nickel content of the weld deposit may have an affect on the SSC resistance of low alloy steels. In fact, NACE standard MR-01-75 prohibits the use of any low alloy steels containing more than 1% nickel in sour service. This arises from SSC studies conducted on nickel containing steel in sour environments. However from other studies, the 1% Ni restriction on welding electrodes content was not substantiated.

4. Inferences on the Susceptibility to Sulphide-Stress Cracking of C and C-Mn Weldments in Sour Environments

The review of the literature indicates that a majority of the studies performed on SSC of weldments in a sour environment have been undertaken on line pipe steels whose compositions are different to pressure vessel steels.

Based on the studies, the idea of specifying a maximum hardness as a means of controlling cracking in steel weldments has appealed to many investigators. In many instances, however, placing too much reliance on a hardness limit of HRC 22 as a criterion for controlling cracking in service performance of steel weldments can be unwise. Kotecki et al and Tanaka et al have shown that SSC can occur at hardness levels less than HRC 22. The SSC and the likelihood of service failures in the weldments depend on the applied stress, microstructure, micro-

structural inhomogeneity, composition, joint restraint and amount of hydrogen entering the weldment in addition to hardness. As the hardness increases, the critical stress required for SSC decreases. Ontario Hydro work suggests that SSC should not be expected in the heavy water tower environment as long as the hardness is less than HV 250 (HRC 22).

The effect of residual stresses on any critical hardness criterion is an aspect that needs further examination. Thus, Kotecki et al showed that weld metal SSC could occur at hardness of HRC 15, if sufficient residual stresses are present. Kihara's work also provides support that as residual stresses increase, the amount of SSC increases. Assessment by Taira et al that residual stresses do not affect propensity to SSC is inconclusive because of the small size of specimens employed. Thus, the evidence suggests a deleterious effect of residual stresses on SSC, but since such evidence is limited, there is a definate need for further studies.

Since there is always some probability of a weld defect remaining in the repair weldment, another area requiring further research is the effect of microstructure and residual stresses on the sulphide fracture toughness parameter K_{ISSC}.

F. TOUGHNESS EVALUATION

The toughness of a weld or HAZ is dependent on such items as filler and base material composition, heat input, preheat and postheat. For repair welds, the toughness, as measured by Charpy Vee notch specimens or Nil Ductility Transition temperature, can be easily assessed using simulated welding procedures for both the heat affected zone and the weld metal.

However, such data is not useful in assessing the integrity of the component or pressure vessel from the point of view of brittle fracture. To carry out an engineering critical assessment for any defect that may be present in a non-stress relieved weldment, one needs to assess fracture toughness as measured by Crack-Tip Opening Displacement (CTOD), J integral and K_{IC} type of tests, and then to carry out an analysis which takes into account the residual stresses that may be present.

The incorporation of residual stresses in the fracture mechanics assessment is not yet well understood. In ferritic materials operating at temperatures above the brittle-ductile transition, and in austenitic steels for example, where crack extension occurs by ductile tearing, there is evidence[21] that residual stress levels have little effect on the load-bearing capacity.

However, in the temperature transition region, it is to be expected that the significance of residual stresses is likely to be highly important. Specific study on the effect of residual stresses incorporated with a fracture mechanics analysis has been carried out by Rybicki and Stonesifer[22] on a weld repair tested in the transition temperature region in the Heavy Section Steel Technology (HSST) programme. Their computed fracture assessment agreed well with the available test data, and suggested that residual stresses had a significant effect on crack initiation and crack arrest. It

was concluded from a linear elastic fracture mechanics analysis, that residual stresses played a major role in the initiation and subsequent arrest of the flaw in this vessel.

However, it has been argued that since most pressure vessels and piping components operate at a tempreature where fracture is in a ductile manner, the application of LEFM methodology leads to very conservative predictions. Even the general yielding fracture mechanics approach, based on the CTOD method and outlined in British Standards Institutions document PD 6493-1980 has built in conservatism. It has, therefore, been suggested that the failure assessment diagram approach (CEGB R6 Method), developed by the Central Electricity Generating Board in U.K. is the most appropriate since it is applicable to material behaviour that can vary from fully elastic to fully plastic. A more complete description of the methodology is outlined in Reference (23).

G. TYPES OF DEFECTS THAT COULD OCCUR DURING REPAIR WELDING

There is little point in attempting a repair weld if the chances of it being defect-free are not very high. The residual stresses associated with repair welds which have not been stress-relieved will probably reduce the defect tolerance considerably, further emphasising the need for defect-free welds.

Repair welds are usually made on completed structures, and therefore in all cases, it is wise to assume a high level of restraint and to develop a procedure accordingly. In addition, the welder's environment is unlikely to compare favourably with that of the original fabrication, and this may influence the quality of the repair weld. The various defects likely to be encountered are of course the same as those which may occur in any of the original welds in the structure, and will depend on technique and welding process as discussed below.

1. Hydrogen Cracking

This is probably the most likely defect to occur in the heat affected zone of repair welds. If Shielded Metal Arc Welding (SMAW) is used for the repair weld, care must be exercised to ensure that only low hydrogen electrodes are used, and that these are baked in accordance with manufacturer's instructions to give very low hydrogen contents, i.e. less than 5ml H_2/100g of deposited weld metal (measured under mercury) for critical applications. The possibilities of hydrogen cracking are recognized by ASME III, XI and by the Ontario Hydro procedure, which have detailed mandatory anti-hydrogen precautions.

Electrodes should be stored in heated ovens or quivers at the job-site, and removed only immediately prior to their use. Preheat should be applied in accordance with published data, applicable codes or defined procedures and should be maintained after welding has been completed in critical applications until the weld has been dressed to

remove, for example, any sharp notches at weld toes. As previously noted, the half bead technique specifies hydrogen diffusion treatment of 2hr minimum between 232 and 288°C, before the weld is allowed to cool below the preheat temperature.

The tempering or refinement of the heat affected zone alluded to in the previous text will reduce the risk of hydrogen assisted cracking.

It should be noted that consistently low weld metal hydrogen levels are readily obtained with the Gas Metal Arc Welding Process (GMAW) without the need for specialist consumable drying and storage facilities required by other processes. This feature is the result of there being no flux present to contain hydrogen bearing compounds, either as constituents or as a binder to hold the various constituents together. The consumables consist of a solid or hard drawn wire of the appropriate composition with shielding of the weld pool provided by inert or semi inert gas.

2. Lack-of-Fusion and Penetration

These defects could easily occur during repair welding, particularly when welding in difficult access areas, in out-of-flat positions. The use of highly skilled welders is, therefore, required for such situations. Fortunately, such defects are usually easy to detect by non-destructive means in ferritic materials. Gas-shielded processes have generally been more susceptible to this kind of defect than flux-shielded processes, but this should not be the case in the future with the rapid advancement of transistorized power sources coupled with suitable welding procedures capable of providing quality out of position welds.

3. Slag Entrapment

This again is generally avoided by good welding practice, and use of highly skilled welders, and is generally easy to detect by non-destructive methods. Again, the defect is common to those processes producing a slag cover and will not be a problem with gas metal arc or gas tungsten arc processes.

4. Porosity

Again, with good welding technique, this should not be a problem. Slight porosity is more or less inevitable in manual welding, but is not considered harmful. Gross porosity should be readily detectable by non-destructive methods.

5. Solidification Cracking

This is most unlikely to be met when repairing with ferritic SMAW electrodes, except perhaps as crater cracks at run ends. This is easily overcome by a modification to welding technique rather than by any metallurgical or procedural changes. However, it is possible with austenitic electrodes, and care must be exercised to select an electrode and a procedure which will not result in a fully austenitic weld pool. Nickel-based electrodes are also susceptible to solidification cracks. In gas-shielded or flux-cored wire repair welds, solidification cracking could possibly occur, due to excessive dilution, poor bead profile, high travel speed, or welding over other defects which might nucleate solidification cracks. Again, if such defects are known to occur, steps can be taken to overcome them by proper weld procedural control.

H. DISCUSSION

1. Weld Repair Techniques

All the methods have the common aim of providing adequate properties in the weld metal and HAZ without the need for a full post weld stress relief. The heat that is required to provide the necessary metallurgical changes must, therefore, come from an alternative source. The two sources used are a) heat from suitably placed subsequent weld passes (Sections C1,2,3 and 4) and localized external heat sources (Section 5 and 6). The first method is shown in Figure 7 from AMCA data, where the tempering effect of a subsequent weld pass is shown on the HAZ of the preceding weld. Hardness indentation point number 1 is in as deposited weld metal and, with a value of HV 234 compared to the HV 371 and HV386 value of point number 2 and 16 respectively in the base material, illustrates the fact that the weld metal with its lower carbon content is much less hardenable than the base material. Hardness points numbers 2-7 inclusive form part of the HAZ of the first pass that have been reheated above the AC_1 temperature, Figure 1, by the HAZ of pass 2.

As this included a full or partial transformation to austenite on heating, the rapid cooling that follows again results in transformation products with high hardness. The CEGB grain refinement technique (Section C2) occurs in the outer area of this band although it is only visible in Figure 7 in the area that incorporates the weld metal of the first pass (hatched area in figure) where the coarse columnar structure of the as-deposited weld is refined to equiaxed ferrite. The stress relief or tempering heat treatment temperature range (Section C3), has been applied to the area marked "tempered zone" which covers hardness points numbers 8, 11 and 12 with values of HV 258, HV 216 and HV 258 respectively. (Points 9 and 10 are in weld metal and therefore already soft.) The relative narrow width of the zone which occurs with shielded metal arc welding, can be noted from the key to the

macrograph, which is to a scale of 10 times full size, and the precision required in the placement of the temper bead reported in reference (5) is confirmed. Increasing the heat input of the second layer will result in a broader temper zone which would allow it to more readily coincide with the HAZ of the previous layer.

The final three hardness points 14, 15 and 16 have increasing hardness of HV 296, HV 301 and HV 386 respectively, indicating that the lower temperatures experienced by these areas are less effective in providing a satisfactory temper.

Increasing preheats would also tend to widen the tempered zone and reduce the cooling rate as shown in Figure 8 where curves of cooling rate vs. preheat for various welding heat inputs have been superimposed on a hardenability curve, mean maxumum hardness vs. cooling rate, for a A516 Gr. 70 type steel of Japanese origin. The cooling rates were calculated using $\frac{dT}{dt(540)} = B_{3D} \frac{(T-To)^2}{E}$ from reference (24) and the hardenability curve is obtained from AMCA data.

To show the effect of preheat, consider the 1.2 kj/mm heat input curve of Figure 8 when the preheat is 20°C, the cooling rate would be 36°C/s (at 540°C) which would result in a maximum HV 416 hardness for the steel under consideration. Now if the preheat is increased to 230°C, the cooling rate becomes 12°C/s and the maximum hardness would be reduced to HV 308. It should be noted that the information given in Figure 8 is to illustrate the beneficial effect of preheat and that the hardness values given will be peculiar to a steel of that composition only.

The Ontario Hydro procedure (Section 4) relies on a combination of the features described above to produce a satisfactory HAZ.

(1) The very high preheat used for the whole repair minimizes the maximum hardness that is achievable in the repair HAZ.

(2) The greater heat input of the second layer (double the first) gives a much wider "temper zone" with which to temper the HAZ of the first layer and allow for any mismatch between the scalloped profiles of the first and second layers.

(3) The maximum hardness of any HAZ occurs in the grain coarsened region close to the fusion boundary and in the case of this procedure, the majority of the second layer and all the subsequent layers will occur in previously deposited weld metal with reduced hardenability because of the low carbon content.

The ASME half bead technique described in Section C1 has been critized for the difficulty of determining when half the first layer has been removed by grinding. This critisicm can also be made of the Ontario Hydro procedure for allowing up to half the first layer to be removed by grinding when necessary in order to provide a satisfactory surface for magnetic particle inspection. Allowing this optional dressing introduces the possibility of a major deviation between the qualification and the actual workpiece because removal of half of the first layer could result in the HAZ of the second layer penetrating too deeply resulting in areas of untempered HAZ. Adjusting the heat input of the second layer locally to cater for any thinning of first layer, would appear impractical and introduce the possibility of further errors.

Even allowing for human factors, welders of reasonable ability are able to produce a weld surface suitable for magnetic particle inspection without any grinding (Figure 9). As the whole procedure evolves around the production of a series of even layers of weld metal of the required thickness, it is suggested that the production of a smooth weld surface, in the necessary positions, is an essential part of the welders qualification for this type of repair welding.

Confidence in the reproduction of results, obtained during qualification, is the major factor in acceptance of the procedure as there is no means of non destructively testing for satisfactory tempering. Strict enforcement of repair welding procedure is, therefore, essential. The maintenance of correct preheat can readily be checked, as can the use of the correct size and type of electrode, by a resident inspector or surveyor. However, ensuring the correct heat inputs is much more difficult as it is a function of current and weld travel speed, the latter being a difficult parameter to determine for manual shielded metal arc welding. An alternative means of specifying heat input for SMAW is to specify electrode run out length or ratio and is based on the notion that it requires a certain heat input to deposit a given size of weld. From AMCA data it is known that it takes 99 seconds to melt 30 cm of a 4.0mm E7018 electrode when the current is 135 A and 53 seconds when the current is 255 A. If both electrodes were deposited over a 15 cm length, run out ratio 0.5, the heat input for the first electrode at 135 A would be 2.05 kj/mm and the second at 255 A would be 2.07 kj/mm if the volts were assumed to be 23V in both cases, a very reasonable assumption. From the above, it can be seen that welds of the same size, (electrodes deposited over the same length), but made with widely varying currents and at different travel speeds are produced with similar heat inputs. The specification of run out length is, therefore, suggested as a means of providing reproducibility to the procedure. Checking the distance between stops/ starts would verify that the correct heat input had been used and checking the pitch of the passes would verify the correct layer thickness (Figure 10).

The areas in which the Ontario Hydro procedure differs from the ASME XI procedure must be viewed as improvements when considering the intended use for repair of heavy water plants subject to sour service conditions. The higher preheat reduces cooling rates and hence the maximum HAZ hardness. The larger diameter electrode for the second layer will give a broader "temper zone" which will more readily

encompass the HAZ of the first layer. Elimination of the grinding requirement removes an area of uncertainty caused by the practical difficulties of gauging and assesing when the required amount of material has been removed.

Automation of the process offers several advantages in addition to increased productivity. Precise reproduction of the qualification parameters on the actual repair should be possible, this would be particularly advantageous around the toe of the repair which has been cited as the most difficult area to apply the tempering technique. The SMAW process would, of course, not be suitable because of interuptions for electrode replacement. Of the continuously fed wire processes flux-cored (FCAW), gas metal arc (GMAW) and hot wire TIG (GTAW) would offer the most potential. FCAW would have the disadvantage of requiring interpass cleaning. GMAW tends to have a deep penetration profile unlike SMAW with its more ideal shallow penetration and rounded HAZ. Changes in shielding gas will offer some possibilities for improvement as will the use of pulsed current with synergic GMAW power sources. GTAW with hot wire can be very productive (5 kg/arc hour) and has a good rounded penetration and HAZ profile, but the equipment tends to be bulky and heavy although this need not be a problem for an automated system. The GTAW process is also able to produce the highest weld metal toughness properties[25].

The previous part of this discussion has dealt with the various components of repair techniques presently being used. The discussion has also illustrated how the present temper bead technique used to repair heavy water towers has utilized and added to components of other techniques to produce a procedure that, has been shown, to achieve a tempered HAZ structure with a hardness value of 250 vpn or less[26]. Additional controls are, however, necessary for these results to be readily reproduced.

Design to avoid SSC in the presence of H_2S has, almost universally, been based on the adoption of the HRC 22 (HV 250) criteria and, field trials and service experience over many years has shown this criteria to have a successful history. However, it is important to note that such field and laboratory trials have been, in the main, on materials of higher strength than A516 Gr. 70, that cracking has been observed to occur in both parent materials and weldments with hardness values below HV 250 and that specifications such as NACE MR-01-75 which invoke this criteria do not recognize any effect of microstructure.

The microstructure is of great importance when it is considered that the region encompassing and surrounding the HAZ of a repair weld can contain all of the following microstructures whose hardness can be HV 250 or less.

As deposited weld metal
Re-austenitized weld metal
Coarse grained HAZ
Fine grained HAZ
Intercritical HAZ
Spherodised HAZ
Parent Material (Normalized)

The effect of microstructure remains largely unexplored and it has been suggested that various microstructures of the same hardness may stand up to service in an H_2S-H_2O environment under the influence of high residual stresses differently. Further corrosion studies are, therefore, needed to clarify the situation.

I. CONCLUSIONS

With adequate attention to welding procedure and welder performance, the high preheat/temper bead technique developed by Ontario Hydro will reduce the heat affected zone hardness levels to HV 250 or less.

J. RECOMMENDATIONS

1. Improvements in Welding Procedural Control

Since the rationale behind improving the properties of the HAZ lies in the superimposition of two weld beads with a defined heat input ratio, then the control of these heat inputs is of fundamental importance. It is recommended that improvements in control be made by the use of run out lengths and pitch of passes to provide measurable parameters between procedure tests and the actual weld repair. With such changes in procedural control, improvements in reproducibility would allow the exploration of tolerances for variations in heat input and the level of preheat used.

The procedure presently used is a major improvement over that defined in the ASME codes as it seeks to eliminate the grinding step which is unsound on a technical basis and also requires increased time and effort. Provisions for grinding are, however, given in the temper bead procedure but this is included only to provide an improved surface condition, when necessary, for hot magnetic particle inspection. The elimination of grinding by greater attention to welder performance at the qualification and repair welding stages would improve the quality of the repairs.

Further improvements in control will be achieved by using automated techniques which would completely eliminate the need for manual welding. Such techniques can be readily repeated from a test piece to actual field repair and, due to the use of a continuous wire system, the number of stop/starts will be reduced. It is known that Ontario Hydro are working towards automating weld repair procedures using gas shielded welding processes.

2. Corrosion Tests

Since it has already been stated that corrosion studies on material types similar to A516 Gr. 70 and especially the susceptibility of weld zones is limited, it is recommended that a suitable corrosion test be agreed between the AECB and Ontario Hydro to validate the application of the temper bead technique. A suggestion for a comparative test to indicate the performance of a temper bead relative to the rest of the weldment is the imersion of the following samples in the solution:

a) Sample in as welded condition; i.e. original weldment without stress relief
b) Sample welded and stress relief; i.e. original weldment
c) Sample temper bead welded; i.e., repair weldment

3. Fracture Assessment

The absence of post weld stress relief heat treatment results in high residual stress remaining in the repair areas. As this can be expected to reduce the critical defect size, a brittle fracutre assessment of any proposed repair is recommended.

REFERENCES

1. ASME Boiler and Pressure Vessel Code, Section XI.

2. ASME Boiler and Pressure Vessel Code, Section III.

3. Holz, P.P. "Half Bead Repairs for In-Service Applications." Paper Presented at Joint ASME/CSME Pressure Vessels and Pipe Conference, Montreal, Canada, June 1978.

4. Alberry, P.J. and Jones, K.E. "Two Layer Refinement Technique for Pipe Welding." Second International Conference on Pipe Welding, London, 1979. The Welding Institute.

5. Olsen, K., Olsen, D.L. and Christensen, N. "Weld Bead Tempering of the Heat Affected Zone." Scandanavian Journal of Metallurgy, 1982, Vol. 11, No. 4.

6. Threadgill, P.L., Garwood, S.J. and Legget, R.H. "Repair Welding of Ferritic Steels without Post Weld Stress Relief." The Welding Institute, Report 9344.01/81/310.5.

7. National Association of Corrosion Engineers; "Material Requirement: Sulphide Stress Cracking Resistant Metallic Material for Oil Field Equipment"; NACE Standard MR-01-75 (1980 Revision); Houston, U.S.A.; 1980.

8. U.S. Patent, Number 3, 087, 715, April 30, 1974.

9. Lastek Engineering, Maidenhead, United Kingdom, Product Literature.

10. Burdekin, F.M. "Heat Treatment of Welded Structures" The Welding Institute, 1969.

11. Carter, C.S. and Hyatt, M.V. "Review of Stress-Corrosion Cracking in the Low-alloy and Low-strength Steels"; Intl. Conf. Stress-Corrosion Cracking and Hydrogen Embrittlement of Iron Base Alloys; June 10-16, 1973; Unieux-Firminy, France; 524-600; 1974.

12. Uhlig, H.H. Corrosion and Corrosion Control. Publ. John Wiley & Sons Inc., New York, 1964.

13. Taira, T., Koboyashi, Y., Inagaki, H., and Watanabe, T. "Sulfide Corrosion Cracking of Linepipe for Sour Gas Service". Paper No. 171, presented at CORROSION/79, Atlanta, Georgia. March 12-16, 1979.

14. Omar, A.A., Kane, R.D. and Boyd, W.K. "Factors Affecting the Sulphide Stress Cracking Resistance of Steel Weldments"; Paper No. 186, presented at Corrosion/81, International Corrosion Forum, NACE, April 6-10, 1981, Toronto, Canada.

15. Kihara, H., Watanabe, M., Horikawa, K., and Inagaki, M. "Studies of Sulfide Corrosion Cracking of High Strength Steels used in H_2S" Problems Prevention and Theories of Corrosion, pp. 235-260. Seventh World Petroleum Congress, Elsevier Publishing Company, 1967.

16. Bates, J.F. "Sulfide Cracking of High Yield Strength Steels in Sour Crude Oil". Materials Protection, Col. 8, No. 1, June 1969, pp. 33-40.

17. Lawson, W.H.S. and Mills D. "Working Within Metallurgical Limitations in the Successful Repair Welding of Power Plant Components". CIM Bulletin, 1981, Vol. 74, No. 831, pp. 100-109.

18. Tanaka, T., Ito, Y., and Nakanishi, M. "The Prevention of Sulphide Stress Corrosion Cracking at Welds in Line Pipe". Proceedings of the 2nd International Conference on Pipe Welding, London, 1979 (Nov.), 1980, Vol. 1, pp. 109-120.

19. Kotecki, D.J. and Howden, D.G. "Submerged-Arc Weld Hardness and Cracking in Wet Sulfide Service". WRC Bull., 184, Welding Research Council, June 1973.

20. Ebert, H.W., "Hard Welds - Their Causes and Preventions" Welding Journal, September, 1971, pp. 636-640.

21. Kanninen, M.F. et al. "Mechanical Fracture Productions for Sensitised Stainless Steel Piping with Circumferential Cracks". EPRI report NP-192, Sept. 1976.

22. Rybicki, E.F. and Stonesifer, R.B. "An LEFM Analysis for the Effects of Weld Repair Induced Residual Stresses on the Fracture of the HSST ITV-8 Vessel". Proceedings, Pressure Vessel and Piping Conference, San Francisco, June 1979, ASME.

23. Harrison, R.P., Loosemore, K., Milne, I., and Dowling, A.R. "Assessment of the Integrity of Structures Containing Defects". C.E.G.B. Report R/H/R6-Rev. 2, 1980.

24. Graville, B.A. "The Principles of Cold Cracking in Welds." The Dominion Bridge Company Limited, Montreal, 1975.

25. Shackleton, D.N. and Lucas, W. "Shielding Gas Mixtures for High Quality GMA Welding of Q. and T. Steels." Welding Journal, Vol. 53, No. 12.

26. Ontario Hydro Research Division Report No. M83-128-H.

BIBLIOGRAPHY

Alberry, P.J., Myers, J. and Chew, B. "Repair of Dungeness "B" Reheat Pipework". CEGB report R/M/N877.

Biefer, G.J. and Fichera, M.J. "Sulphide Stress Cracking Tests on Gas Transmission Line Pipes". Presented at the Symposium on the Effects of Hydrogen Sulphide on Steel, 22nd Annual Conf. of Metallurgists, CIM, Edmonton, Alberta, Aug. 21-24, 1983.

Bruno, T.V. and Hill, R.T. "Stepwise Cracking of Pipeline Steels - A Review of the Work of Task Group T-1F-20"; Paper No. 6 Corrosion/80; March 3-7, 1980; Chicago.

Bryan, R.H. "Test of 6 In. Thick Pressure Vessels, Series 3: Intermediate Test Vessel V-7A Under Sustained Loading." ORNL/Nureg 9, Feb. 1978.

Bryan, R.H. "Test of 6 In. Thick Pressure Vessels, Series 3: Intermediate Test Vessel V-7B." ORNL/Nureg 39, Oct. 1978.

Canonico, D.A. and Holz, P.P. "Half Bead Welding Techniques." Oak Ridge National Laboratory, Report CONF 7805127-1, May 1978.

Canonico, D.A. and Whitman, G.D. "Evaluations of Half-Bead Weld Repair Procedures with Thick-Wall Pressure Vessels." Criteria for preventing service failures in welded structures. Papers presented at JWS 3rd International Symposium Tokyo, 26-28 Sept. 1978., Publ.: Tokyo, Japan Welding Society, 1978.

Coe, F.R. "Welding Steels without Hydrogen Cracking." Welding Institute, 1973.

Egan, G.R. "Repair Welds without Postweld Heat." IIW Document X-826-76 and IX-1005-76.

Goins, W. and Merrick, E. "Weld Repair of HSST Vessel V-7." DVS Berichte 52, 3rd International Conference on welding in nuclear engineering, Hamburg, 28/29 Nov. 1978.

Gooch, T.G. "Hardness and Stress Corrosion Cracking of Ferritic Steel". The Welding Institute Res. Bulletin, 1982, Vol. 23(8), pp. 241-246.

Gooch, T.G. "Repair Welding with Austenitic Stainless Steel MMA Electrodes." Met. Con., Nov. 1980, p. 622.

Higuchi, M., Sakamoto, H., and Tanioka, S. "A Study on Weld Repair Through Half Bead Method". IHI Engineering Review, 13 (2), April 1980, pp. 14-19.

Kiefner, J.F. "Pipeline Defect Repair Procedures." Proceedings 6th Symposium on Line Pipe Research, Houston, 1979. Publ.: American Gas Association.

Kozulin, M.G., Moshnikov, V.S., Fil Chenkov, D.I. and Volkova, A.P. "The Multiple Repair of Welded Joints in Low Carbon Steels." Welding Production Vol. 24, No. 6, June 1977, pp. 52-54.

Landerman, E. and Grotke, G. "Residual Stress Considerations in Weldments for the Nuclear Industry.: Weldments: Physical Metallurgy and Failure Phenomena. Proceedings 5th Bolton Landing Conference, Aug. 1978.

Livshits, L.S. et al. The Influence of the Welding Technology on the Resistance of Welded Joints to Corrosion Cracking in an Environment Containing Hydrogen Sulphide. Welding Research Abroad, Vol. 24, No. 6, 1978, pp. 68-71.

Ludden, G.C. "Field Repairs Get Refinery Operation Gong on Time." Welding Design and Fabrication, Vol. 52, No. 11, Nov. 1979, pp. 59-62.

Nakazawa, T. and Tanimura, M. "SSCC in Welded Parts of High Strength Steels" published by Nippon Kokan Technical Research Center of Kabushiki Kaisha, October 1978.

National Association of Corrosion Engineers; "Test Method: Testing of Metals for Resistance to Sulphide Stress Cracking at Ambient Temperatures"; NACE Standard TM-01-77; Houston, U.S.A.; 1977.

Pelli, R. and Rintamaa, R. "Properties of Heat Affected Zones in Repair Welds of Pressure Vessel Steels." Proceedings, 4th International Conference, Welding in Nuclear Engineering, Aachen, Nov. 1982. Publ.: Dusseldorf, W. Germany.

Prince, J.W. "Integrity of Non-Post-Weld Heat Treated Heavy Section Weld Repairs". Presented at the Welding in Energy Related Projects Conference in Toronto, Sept. 21-23, 1983.

Rees, A.J.E. "Problems with Pressure Vessels in Sourgas Service (Case Histories)." Materials Performance, Vol. 16, No. 7, July 1977, pp. 29-33.

Schmid, G.C. "The Resistance of Nickel Containing Steels and Weld Metals to Sulphide Stress Corrosion Cracking". Presented during Corrosion 1979, March 1979, Atlanta, Georgia.

Smith, G.C. and Holz, P.R. "Repair Weld Induced Residual Stresses in Thick Walled Steel Pressure Vessels." ORNL/Nureg/TM-153, Oak Ridge National Laboratory, Tennessee, 1978.

Stephenson, G.G. "Welding Practices in Fossil-Fired Units." Welding Technology for Energy Applications, Publ: Oak Ridge National Laboratory, 1982.

Tuttle, R.N. "Guidelines Aid in Designing for H_2S Service"; Oil and Gas Journal, 1978, Dec. pp. 108-116.

Tuttle, R.N. "Guidelines Aid in Designing for H2S Service." H2S Corrosion in Oil and Gas Production - A Compilation of Classic Papers, Editors: R.N. Tuttle and R.D. Kane. Publ: National Association of Corrosion Engineers (NACE).

Treseder, R.S.; "Oil Industry Experience with Hydrogen Embrittlement and Stress Corrosion Cracking". Presented at the Conference held in Unieux-Firminy, France, June 12-16, 1973. Stress Corrosion Cracking and Hydrogen Embrittlement of Iron Base Alloys. Published by NACE.

Whitman, G.D. "HSST Programme, Quarterly Progress Report for April-June 1977." ORNL/Nureg/TM-147.

Whitman, G.D. and Bryan, R.H. "HSST Programme, Quarterly Progress Report for July-September 1977." ORNL/Nureg/TM-166.

Whitman, G.D. and Bryan, R.H. "HSST Quarterly Progress Report for July-September 1978." Oak Ridge National Laboratory Reoprt ORNL/Nureg/TM-275.

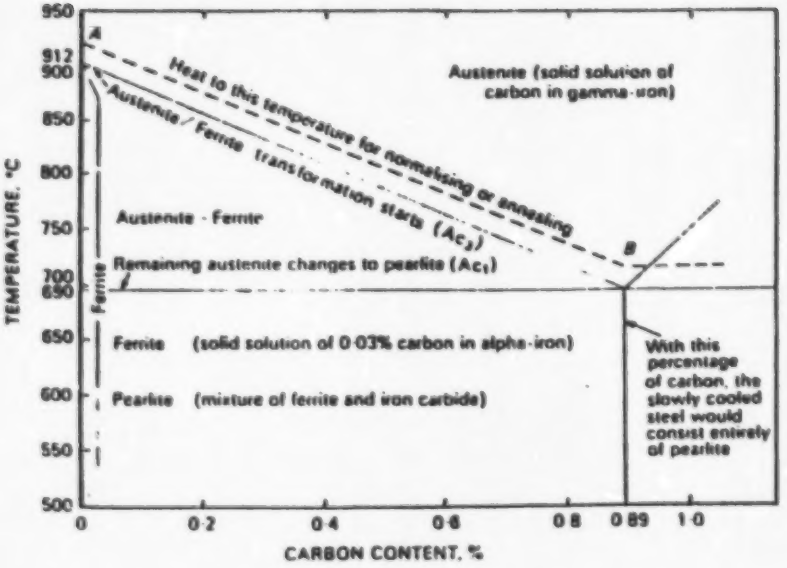


Figure 1: Iron Carbon Equilibrium Diagram

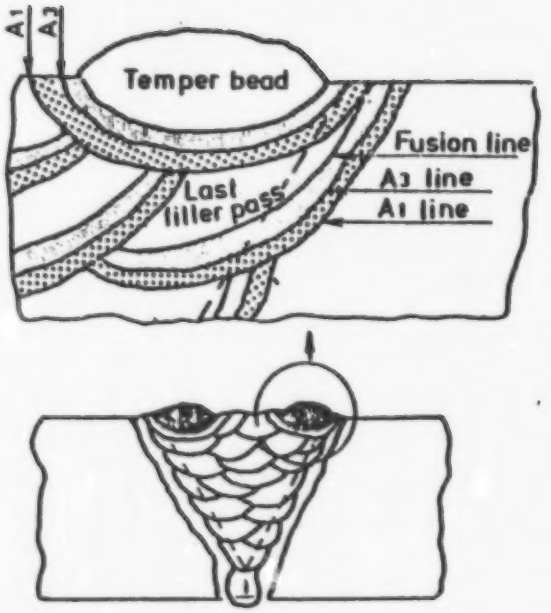


Figure 2: Temper Beads (schematic)

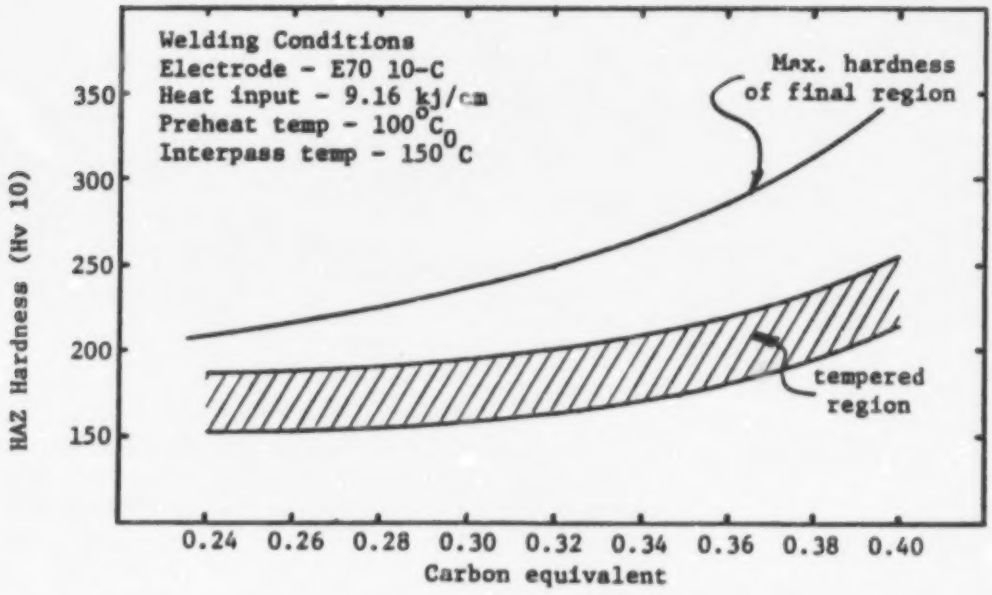


Figure 3: Correlation of carbon equivalent and maximum hardness in HAZ of girth weld joint.

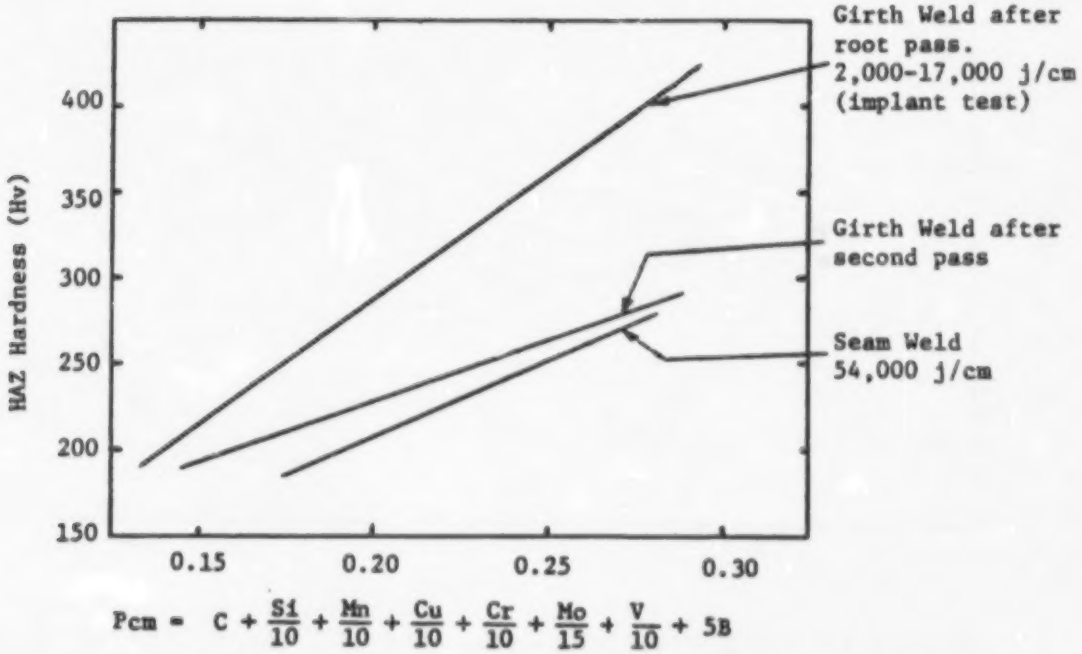


Figure 4: Relationship between maximum hardness of linepipe welds and chemical composition.

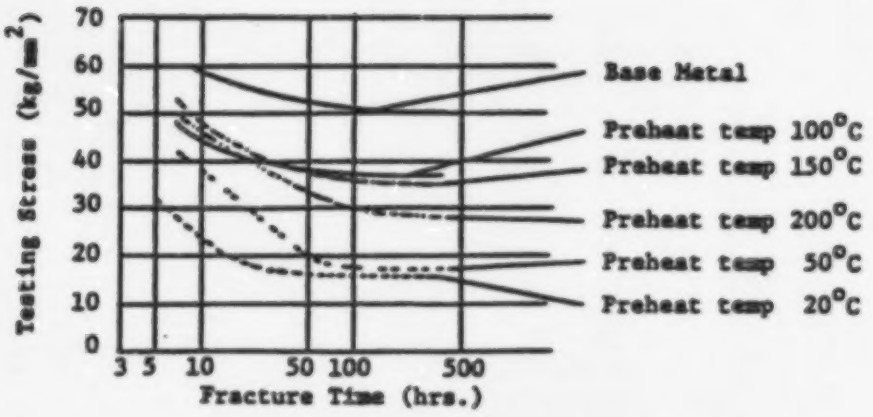


Figure 5: Relation between sulphide corrosion cracking of heat affected zone of the newly developed steel and preheating temperature.

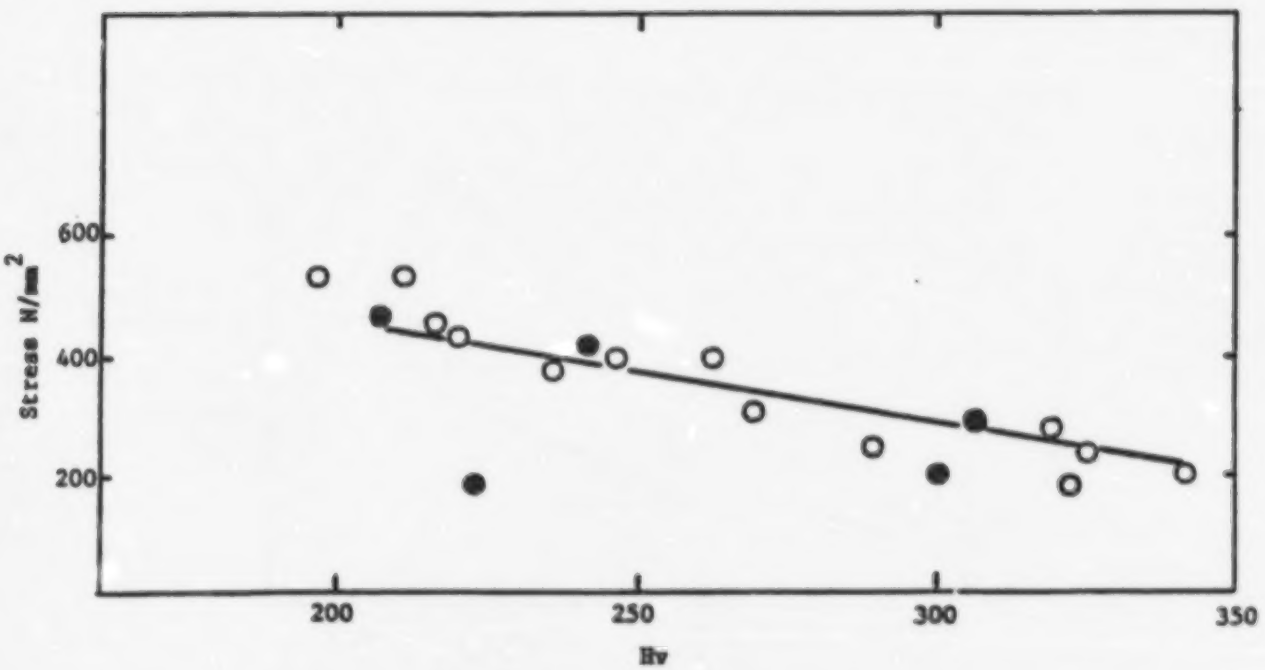
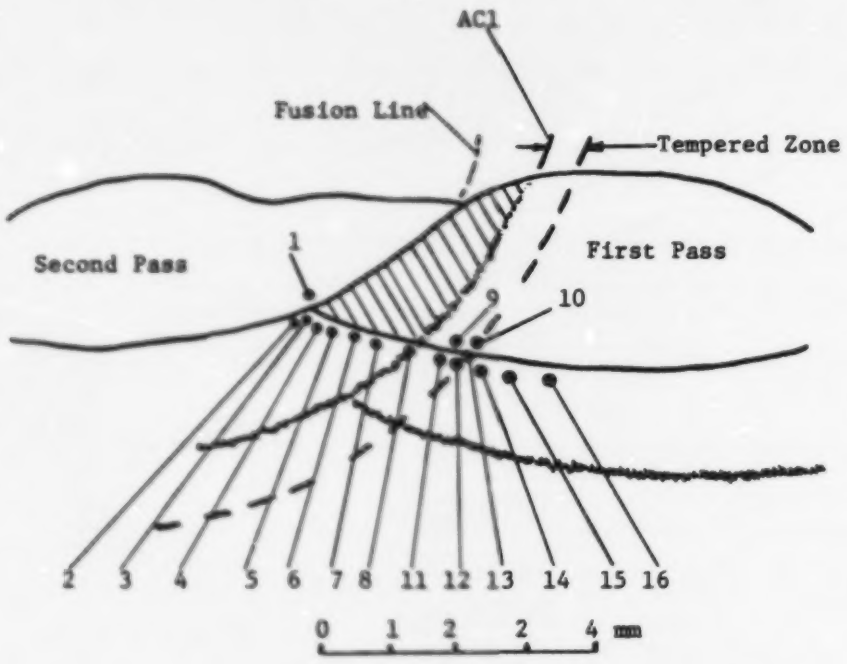


Figure 6: SSCC susceptibility after SR treatment (SR conditions: 625°C x 30 min, furnace cool). Environment: 5% NaCl + 0.5% CH_3OOH aqueous solution + H_2S; test duration 200 hr.

○ = as welded ● = after SR



Point No.	Hv 50g.
1	234
2	371
3	312
4	343
5	378
6	324
7	350
8	258
9	213
10	237
11	216
12	258
13	
14	296
15	301
16	386

Figure 7: Effect of Tempering Pass

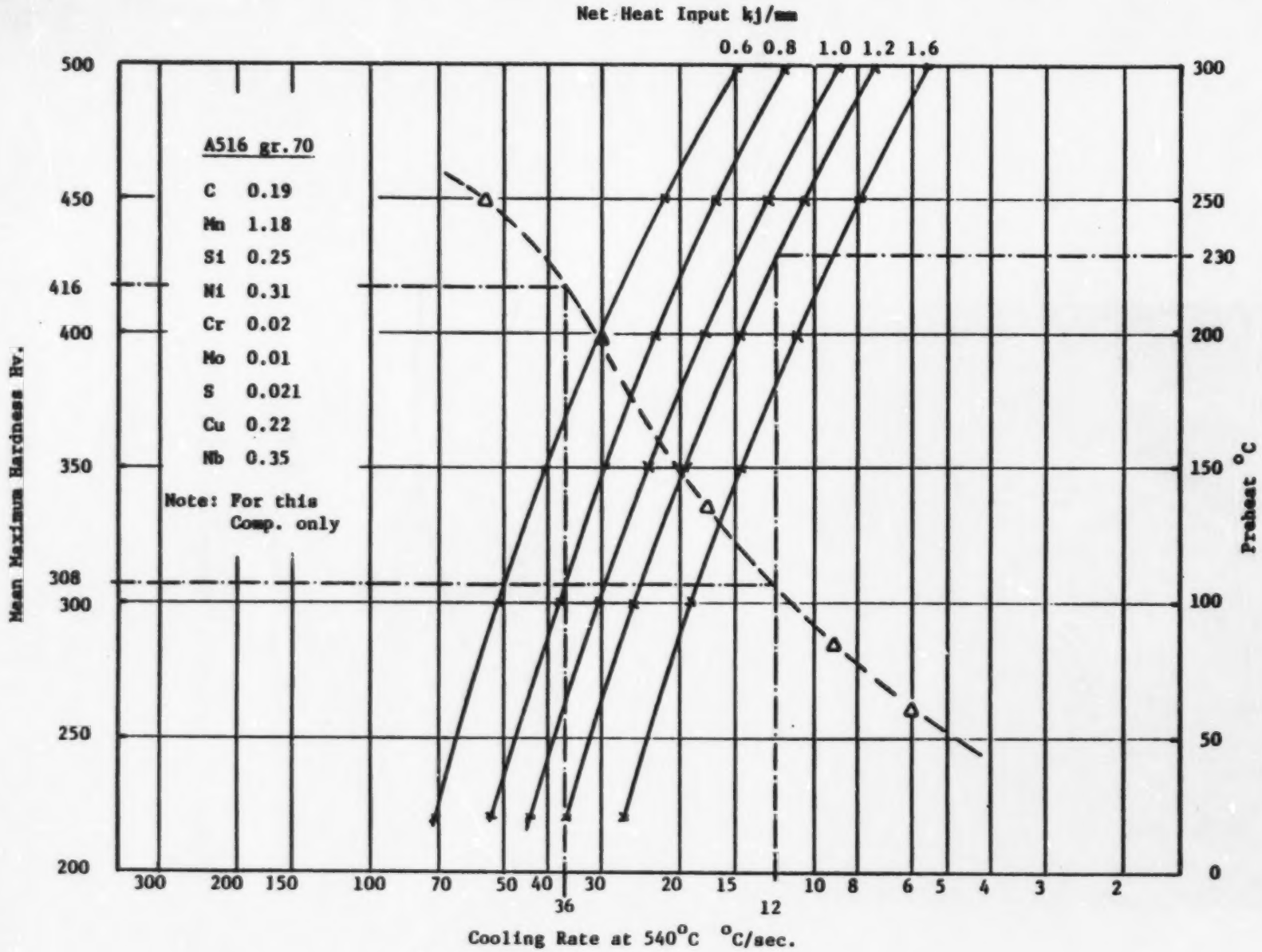


Figure 8: Hardenability Curve

As-Welded Surface

FIGURE 9

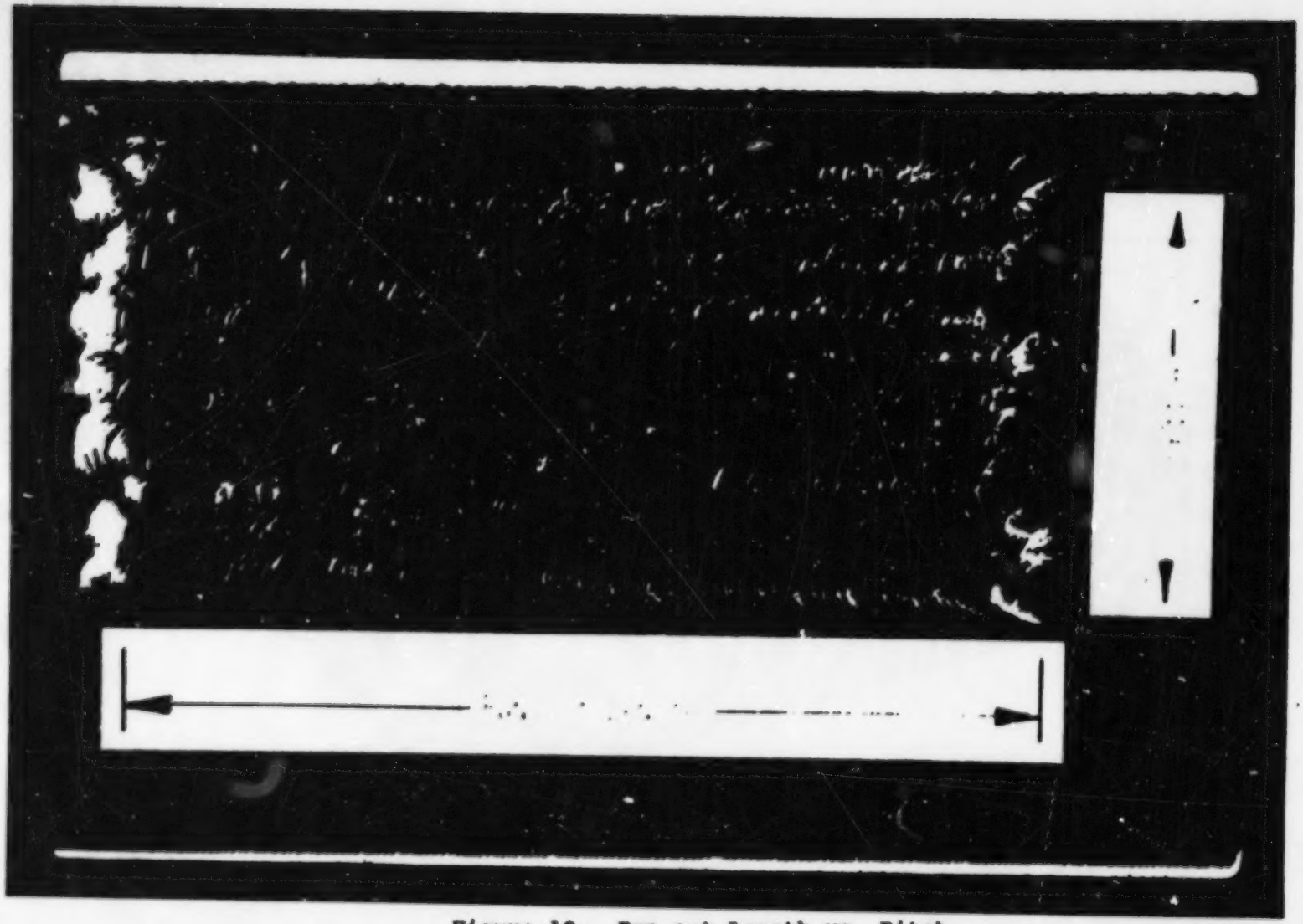


Figure 10: Run out Length vs. Pitch

ontario hydro

Appendix 1 standard specification

class number

PN - 636 - 03

Superseding
PN - 636 - 82

Issued
February 1983

PRESSURE CODE WELDING PROCEDURE
(Temper-Bead Technique)

Base Metals	P No 1 Group 2
Base Material Thickness (max)	70 mm (2.75 in)
Allowable Depth of Repair (max)	35 mm (1.375 in)
Process	SMAW
Filler Metal	E7018
F-Group	F4
Positions	All
Progression	Upward in 3G Position
Preheat	230°C minimum
Postweld Heat Treatment	230°C to 290°C

A SCOPE

A-1 This procedure shall not be used for repair welding of nuclear components.

A-2 This procedure specification, which is intended for use by Ontario Hydro personnel only, is applicable to the repair welding of pressure vessels used in a corrosive environment such as in heavy-water plant, to depths of 35 mm (1.375 in) maximum, by the temper-bead (TB) technique, without having to resort to high temperature postweld heat treatment (PWHT). The specification also covers the general requirements for qualification of welders.

A-3 The TB procedure is not intended to be routinely supplanted for PWHT. Consequently, before a decision is made to apply the technique, the impracticability of PWHT must be established. Also, because the TB technique requires high standards of workmanship and control, assurance must be

obtained that adequate equipment is on hand to control electrode quality and base metal temperatures, as required herein.

A-4 The procedure has the approval of the Pressure Vessels Safety Branch of the Ministry of Consumer and Commercial Relations (MCCR). The Branch's WPS number on this specification indicates approval of the procedure.

A-5 This welding procedure is based on the requirements of the following:

Standard of the CANADIAN STANDARDS ASSOCIATION (CSA),

B51-M Code for the Construction and Inspection of Boilers and Pressure Vessels

Standards of the AMERICAN SOCIETY OF MECHANICAL ENGINEERS (ASME),

Boiler and Pressure Vessel Code
Section III, Nuclear Power Plant Components
Section VIII, Pressure Vessels, Division 1
Section IX, Welding and Brazing Qualifications
Section XI, Rules for In-Service Inspection of Nuclear Power Plant Components

B REFERENCES

B-1 Reference is made in this specification to the following standards, the latest issues, amendments and supplements of which shall apply unless otherwise indicated.

Standard of the AMERICAN WELDING SOCIETY (AWS),

A3.0 Welding Terms and Definitions

Standard of the AMERICAN SOCIETY OF MECHANICAL ENGINEERS (ASME),

Boiler and Pressure Vessel Code
Section II,
Part A - Material Specifications, Ferrous Materials

SA-516 Carbon Steel Plates for Pressure Vessels for Moderate and Lower Temperature Service

Part C - Welding Rods, Electrodes and Filler Metals

SFA-5.1 Carbon Steel Covered Arc Welding Electrodes

C PROCEDURE QUALIFICATION

C-1 Qualification tests for the procedure, which have been approved by the MCCR, are recorded on the attached Q-1 form. This document will be considered to be part of this specification.

C-2 This procedure has been qualified with a 35 mm (1.375 in) deep groove 13 mm (0.5 in) wide at the root and a 60° included angle and a length of 457 mm (18 in). Under the requirements of ASME Section XI, the geometry of the repair cavity is an essential variable, as described in Clause E-7.

C-3 The procedure is qualified in accordance with the requirements of Article IWB-4000 of Section XI of the ASME Boiler and Pressure Vessel Code.

D PERFORMANCE QUALIFICATION

D-1 Personnel who perform pressure code welding in accordance with the accompanying specification, shall have first been tested and approved by the MCCR.

D-2 The test positions shall normally be the 2G (horizontal) and 3G (vertical), with upward progression in the 3G.

D-3 If the repair weld is to be done where physical obstructions impair the welder's ability to perform, the welder shall demonstrate his ability to deposit sound weld metal in the positions required, using the same parameters and simulated physical obstructions as are involved in the repair. In this case, the weld shall be examined by radiography or ultrasonic and magnetic particle inspection in accordance with ASME Section III, Subsection NB-5000.

D-4 Before performing a repair, the welder shall become thoroughly familiar with the required sequence of beads and layers of weld deposit, the need for careful control of welding electrode condition, metal temperature, and bead size. This procedure specification incorporates this information, and shall be supplied to the welder prior to commencement of the work.

E ESSENTIAL VARIABLES

The procedure covered by this specification is valid only within the limits specified under Essential Variables, Sections E-1 to E-8. Where changes to one or more of these variables are necessary for a particular application, the procedure to be followed, although similar in all other respects to that covered here, shall be considered to be a new procedure. As such, it requires separate qualification by the MCCR.

E-1 Base Metal

E-1.1 The base metal shall be steel that conforms to the requirements for materials listed under P No 1 Group 2 of Table QW-422 of Section IX of the ASME Boiler and Pressure Vessel Code.

E-2 Base-Metal Thickness Range and Depth of Repair

E.2.1 The thickness range shall be from 25 mm (1 in) to 70 mm (2.75 in).

E-2.2 The maximum nominal depth of repair weld shall be 35 mm (1.375 in).

E-2.3 The depth of repair shall not exceed one half the base metal thickness.

E-3 Process

E-3.1 The process shall be manual shielded metal arc welding (SMAW).

E-4 Filler Metal

E-4.1 The filler metal shall conform to ASME classification F4 listed in Table QW-432 of Section IX, but shall be restricted to the use of E7018 electrodes only.

E-4.2 All electrodes used to perform this repair procedure shall be in conformance with the requirements of NB-2400 of Section III of the ASME Boiler and Pressure Vessel Code. They shall be identified in compliance with the requirements of Subarticle NB-2150.

E-4.3 Electrodes shall be limited to a copper content of 0.10 percent maximum and a phosphorous content of 0.015 percent maximum (as deposited).

E-4.4 Prior to use, the electrodes shall be baked and stored in accordance with Clause G-2.

E-5 Positions and Progression

E-5.1 Welding may be done in all positions, with upward progression in the 3G position.

E-6 Preheat and Interpass Temperature

E-6.1 The cavity or area to be repaired by welding, and a full encircling band around the cavity or area, shall be preheated to a minimum of 230°C.

E-6.2 The width of band to be preheated shall be 3 times the thickness (3T) of the component to be welded, but need not exceed a width of 254 mm (10 in).

The band of preheat shall be shaped symmetrically so as to induce the minimum practical level of distortion into the component due to differential thermal expansion. In the case of a cylindrical vessel the band of preheating should, whenever practical, encircle the girth of the vessel.

E-6.3 The minimum preheat temperature shall be maintained for at least 30 min before welding is started.

E-6.4 The maximum interpass temperature shall be 290°C.

E-7 Geometry of Repair Cavity

E-7.1 The ratio of cavity top width to cavity depth shall not be less, at any point, than that identified in Clause C-2, viz W/D 1.5. If the included angle is less than 60°, then the cavity bottom width shall be increased so as to afford adequate access for electrode manipulation.

E-8 Postweld Heat Treatment

E-8.1 At the completion of welding, the 3T band as defined in E-6.2 shall be maintained in the range of 230°C to 290°C for at least 2 h.

G REPAIR PROCEDURE

G-1 Preparation for Welding

G-1.1 Preheat in accordance with Clause E-6.1 before arc air gouging.

G-1.2 The removal of defects by thermal methods shall be in accordance with the requirements of "Procedure for Air Carbon Arc Gouging and Cutting", Section 9 of the Ontario Hydro Welding Manual.

G-1.3 Materials shall be removed by a mechanical method from all thermally processed areas.

G-1.4 A minimum of 1.6 mm (0.062 in) material shall be removed by grinding from the cavity to be repaired.

G-1.5 The depths of materials to be mechanically removed shall be determined by actual measurement from a generally smoothed area produced by mechanical removal of irregularities resulting from the thermal removal process. All corners and edges shall be rounded off.

G-1.6 After final grinding, the affected surfaces, including surfaces of cavities prepared for welding, shall be examined by the dry powder magnetic particle method in accordance with NDE-4N to assure that the indication has been completely removed. Following MT, demagnetization should be performed to prevent arc wander.

G-1.7 Indications detected as a result of the excavation, that are not associated with the defect being removed, shall be evaluated for acceptability in accordance with IWA-3000 of Section XI of the ASME Code.

G-2 Electrode Storage

G-2.1 Before use, the covered electrodes shall be baked at 425 $\pm$ 15°C for 30 - 60 min, proceeding as follows:

G-2.1.1 The electrodes shall be placed in the baking oven, the temperature of which, at the start of the bake cycle, does not exceed 150°C.

G-2.1.2 To ensure that all electrodes are subjected to the complete baking cycle, a thermocouple shall be located in the centre of the pile of electrodes in the oven. The height of the pile shall not exceed five times an electrode diameter.

G-2.1.3 The oven temperature shall then be raised, from 150°C to 260°C, at any rate of rise.

G-2.1.4 From 260°C, the temperature shall be further raised, at a maximum rate of 165°C/h, to 425 $\pm$ 15°C, and then held at this temperature for 30 - 60 min.

G-2.1.5 After the 30 - 60 min baking period, the oven shall be allowed to cool. Before the temperature reaches 105°C, the electrodes shall be transferred to holding ovens.

G-2.1.6 The combined times of temperature raising, temperature holding, and cooling, above 260°C, shall not exceed 5 h.

G-2.1.7 The holding oven temperature shall be maintained between 105°C and 175°C.

G-2.2 During the repair period, the holding oven shall be located in the repair area.

G-2.3 Electrodes removed from the holding oven and then exposed to the atmosphere for between 20 min and 4 h shall be returned to that oven for at least 8 h before-use.

G-2.3.1 Electrodes exposed to the atmosphere for a period in excess of 4 h shall be reprocessed in accordance with Clause G-2.1 above. Electrodes shall not be processed more than once for temper-bead work.

G-3 Electrical Characteristics

G-3.1 Direct current, reverse polarity shall be used.

G-4 Welding Technique

G-4.1 Preheat in accordance with E-6. The 3T band shall encompass the entire circumference of the vessel. Thermocouples and recording instruments shall be used to monitor the preheat and interpass temperature.

G-4.2 The cavity shall be buttered using 2.4 mm (3/32 in) maximum diameter electrode as shown in Dwg SSD 1072, Step 1.

G-4.2.1 Following coverage of the entire cavity surface, by the first layer, grinding may be done to facilitate interlayer magnetic particle examination (see Clause G-9.1). If grinding is necessary, the first layer thickness shall not be reduced by more than one half.

G-4.3 The second layer shall be deposited with a 3.2 mm (1/8 in) diameter electrode, as shown in Dwg SSD 1072, Step 2. The maximum bead width shall not be more than 2-1/2 times the electrode core diameter. A weaving movement shall not be used in deposition of the first two layers. The heat input for each bead of the second layer shall be twice that for each bead of the first layer.

Heat input measured in J/mm = $\frac{\text{Voltage x Amperage x 60}}{\text{Travel Speed (mm/min)}}$

G-4.4 The correct placing of each of the first two weld layers is achieved by directing the arc at the toe of each preceding bead. More than 50 percent overlap of the weld bead on the previously deposited bead is not acceptable. The weld beads extending beyond the edge of the cavity must be ground off on completion of the repair.

G-4.5 Subsequent layers shall be deposited with welding electrodes no larger than 4 mm (5/32 in) diameter. Bead deposition shall be performed in a manner shown in Dwg SSD 1072, Step 3.

G-4.6 The completed weld shall have at least one layer of weld reinforcement deposited and then removed by mechanical means, making the finished surface flush with the surface of the vessel surrounding the repair.

G-4.7 At the completion of welding, the 3T band, as defined in E-6.2, shall be maintained in the range of 230°C to 290°C, for at least 2 h.

G-5 Peening

G-5.1 Peening shall not be permitted.

G-6 Identification

G-6.1 Each repair shall be identified by the welder's letter, number or symbol by means of an approved heat-resistant paint.

G-7 Interpass Cleaning

G-7.1 All slag shall be removed before the succeeding bead is deposited.

G-8 Interruption of Welding

G-8.1 Welding should preferably be continuous. If welding is interrupted, the preheat shall be maintained if possible. If the preheat cannot be maintained, the preheated area must be given a baking treatment of 230°C to 290°C for 2 h and wrapped in an insulating blanket.

G-8.2 When welding is resumed, the preheat requirements of E-6 must be observed.

G-9 Inspection

G-9.1 All layers shall be examined by the dry powder magnetic particle method NDE-4N and demagnetized before welding.

G-9.2 The repair area and the 3T band shall be examined nondestructively after the weld has been at ambient temperature for a period of 48 h minimum. The nondestructive examination of the repair welded region shall include radiography, if practical, ultrasonic and magnetic particle examination.

G-9.3 Areas from which weld thermocouples have been removed shall be ground and examined by the dry powder magnetic particle method NDE-4N.

WELD DATA

SMAW - DC, Reverse Polarity - E7018

Electrode Diameter mm	(in)	Welding Current (A)	Arc Voltage (V)
2.4	(3/32)	80-130	21-24
3.2	(1/8)	100-160	21-24
4.0	(5/32)	130-200	22-25

APPENDIX A

Discussion of Temper-Bead Welding Metallurgy

Postweld heat treatment (PWHT) is normally considered to be necessary for the achievement of satisfactory properties and performance in heavy, restrained welds. PWHT, by softening the weld zone, improves resistance to cracking, promotes diffusion into the atmosphere of hydrogen (a potent crack promoter) dissolved in the weld, and allows for relaxation of residual stresses. The special features of the temper-bead procedure are intended to achieve similar results, as far as is practicable, to those possible with PWHT. Sloppy or inadequate performance of any step in this procedure will result in a repair which may not perform adequately in service.

With the sequential deposition of each bead of the first layer of weld deposit, the base metal immediately underlying each bead is heated, and subsequently cools. To minimize the hardening effect on the heat-affected zone (HAZ) of the base metal, by this localized heat treatment, a high-temperature preheat is needed. In spite of this preheat treatment, however, the HAZ properties, following deposition of the first weld-deposit layer, remains unsatisfactory. A second layer is, therefore, required to soften and toughen the HAZ. In order for this to occur, the first layer must be of an accurately controlled and uniform thickness; thick enough for the second layer not to melt through, but not enough to prevent the HAZ being softened (tempered) as each bead of the second layer is deposited. Further, studies have shown that the proper superposition of the thermal effects of the two layers will occur if both are deposited as stringer beads, and the electrode used for the second layer is one size larger than that used for the first layer. Weaving is not permitted because not only is there the tendency for a coarser and more brittle crystal structure to occur in the HAZ, but control of the thicknesses of the first two layers is more difficult to maintain from welder to welder.

The coating of any shielded metal arc welding electrode will absorb moisture from the atmosphere if permitted to do so. This moisture is decomposed by the arc, and the free hydrogen produced becomes dissolved in the weld metal. Hydrogen and hard zones in and around a weld bead continue to be the most common causes of cracking of steel welds. An adequately low risk of formation of such cracks in temper-bead repair welds can be secured only if each electrode used has been specially heat treated (as detailed in the specification) to achieve maximum dryness, and then held at elevated temperature to

maintain dryness until fusion. Accurate carrying out of preheating and bead/layer deposition sequence is also essential to prevent the formation of any hard spots with which hydrogen can react. Finally, to complete the procedure, the repair area needs to be given a low temperature heat treatment immediately after welding, to disperse any hydrogen inadvertently introduced.

It must be kept in mind while welding that every weld bead in the buttering layers is performing an essential step in the heat treatment of the repair. Therefore, every weld bead which is improperly placed, or deposited with incorrect conditions of temperature or welding technique, can leave behind it a strip of metal having a permanently incorrect metallurgical structure. To minimize the chance of this happening, agreement should be secured with all welders involved with the repair as to the sequence in which the beads of the two buttered layers will be deposited, to ensure that the optimum bead overlap pattern can and will be obtained throughout the cavity shape at hand.

FORM Q-1: RECORD OF WELDING PROCEDURE QUALIFICATION TESTS
(Q-1 Form Revised January 1983)

Specification	Test Date	Process(es)	Lab Report No.
W-030-83	March 9/81	SMAW	SQ81-24-K

Base Materials	P-Nos.	Test Piece(s), (if pipe, dia. and wall)
SA516-GR70	P1-GR2	2-3/4" Plate

Thickness Range Qualified	Pipe OD Range Qualified	Filler Metal(s) Type or Analysis	F-No(s)
35-70 mm (1.375-2.75 in)		E7018	4

Weld-Metal(s) Analysis	A-No.
	1

HEAT TREATMENT

Preheat Temp.	270°C (520°F)
Interpass Temp. Min:	Max: 270°C (550°F)
Postheat Temp.	270°C (520°F)
Holding Time	2 h

FLUX ATMOSPHERE

Flux: Neutral ☐ Alloying ☐	Flux Trade Name	Purging ☐

Shielding Gas(es)	Gas Trade Name	Flow Rate(s)
		cfh

CHARPY IMPACT TESTS Specimen Temperature: −46°C

Specimen, Notch-Root Location		V-Notch Impact Energy (J)	Average Energy (J)	Lateral Expansion (mm)	Ductile Fracture (percent)
1	WM	13		0.33	30
2	WM	38		0.62	34
3	WM	44	31.6	0.79	21
4	BM	20		0.38	16
5	BM	13		0.25	11
6	BM	22	18.3	0.44	11
7	HAZ	52.5		0.99	44
8	HAZ	14		0.25	11
9	HAZ	40	35.5	0.69	48

WELDING PROCEDURE

Pass.	Single ☐ Multiple ☒
Arc:	Single ☒ Multiple ☐
Groove Position (if vertical, state upward, or downward)	
	Forehand ☒ Backhand ☐

TENSILE TESTS

Specimen	Dimension (mm) Width, OD	Thickness	Area (mm²)	Ultimate Force (kN)	Ultimate Stress (MPa)	Failure Character	Failure Location
	12.80		128.6	71.9	560.8	Ductile	WM

BEND TESTS

Specimen, Test Type	Results, Comments
Side Bends (4)	Satisfactory

FILLER METALS

Travel mm/min	Deposit mm/min	Feed mm/min

Sizes A-2.4 mm (3/32 in)
B-3.2 mm (1/8 in)
C-4.0 mm (5/32 in)

Trade Names
Atom Arc

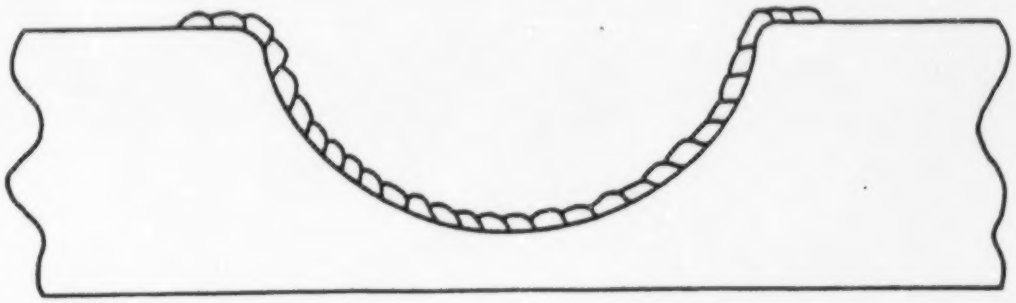
ELECTRICAL

Dc ☒ Ac ☐	Polarity	Amps Range	Volts Range
	Rev	A80, B125, ~~C140~~	A23, B23, C23

DRAWINGS

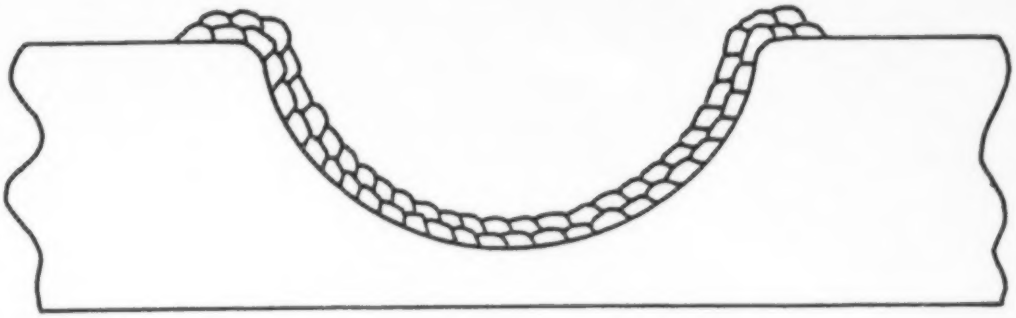
GENERAL

Welder, Operator	B. Jennings	Clock No.	Stamp No. HW-U
Ministry Witness	B.H. Thomas	Ministry Examiner	G. Muirhead
Ontario WPSNo. Date	F638.5 June 3/82	Ontario Hydro Representative	P. Green



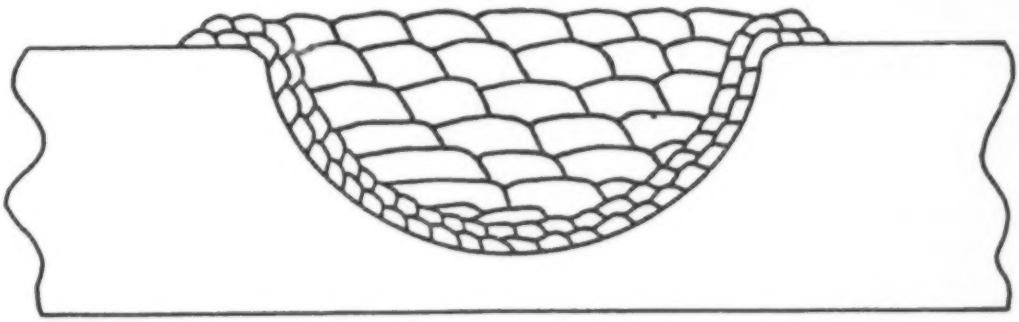
STEP 1

BUTTER CAVITY WITH ONE LAYER OF WELD METAL USING 2.4 mm ($\frac{3}{32}$ in) DIA ELECTRODES



STEP 2

BUTTER FIRST LAYER WITH ONE LAYER OF 3.2 mm ($\frac{1}{8}$ in) DIA ELECTRODES



STEP 3

FILL REMAINDER OF CAVITY USING NORMAL FILL PROCEDURE WITH 4 mm ($\frac{5}{32}$ in) DIA ELECTRODES

DRAWING NO SSD1072 R0

TEMPER BEAD WELDING

DRAWING . . . . . 1 OF 1

FOR ONTARIO HYDRO SPECIFICATION PN-636-83